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Volume II



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Andrea D'Angelo
Mauro Sassu

The Abbey «Badia di San Savino» is a medieval monument complex dominating the Pisan plain near the Arno river. This monastery's buildings surround the southern and western slopes of a presumably man-made embankment, atop which stands a Romanic church, flanked by its imposing bell tower. The northern side has been eroded by landslides, while the eastern is sustained by a retaining wall with stone barbicans. The aim of the study presented herein is to interpret the data on the geometric configuration and construction materials of this religious centre. Such data has been compiled via architectonic survey and on-site inspection of the current state of the buildings, supplemented by a wide-ranging inquiry into historical archive documents, including iconographic and bibliographic sources.

The most important stage of this preliminary study has been the historical analysis: the history of the S. Savino complex is marked by many alterations and modifications to the original structures, presumably carried out to adapt them to the demands of different ages and different functions (Ceccarelli Lemut and Garzella, 1996 —Pazzagli, 1985— Redi, 1984): the original monastery has successively undergone transformation to a strategic fortress of the Pisan Republic, to an estate of the Order of the Knights Saint Stephan, and finally to residential dwellings. From this historical evolution it is possible to recognize various construction techniques used in each period. Moreover, from the static perspective, the structure faces the eastern front of the embankment, a front formed by the monastery's terminal furthermost side and a high retaining wall, against which lean a secondary entry tower, a recently added concrete buttress and three centuries-old stone barbicans.

By means of computerised F.E.M. analysis of the masonry structures, it has been possible to confirm some assumptions about the different time settings of several of the restructuring operations in this part of the Abbey, as well as their static roles. Such an analysis has moreover made it possible to improve our understanding of the structural behaviour of masonry erected with age-old construction techniques and to propose appropriate restoration operations for consolidation of the structures, currently in a state of severe deterioration.

Historical remarks: diachronic analysis

The oldest iconographic sources date back to the 17th century.[1] Thus, for the period elapsed from the monastery's origins up to that time, written historical sources and the hypotheses emerging from historical studies on the building were used for reconstruction of its chronology:[2]

— in the early 11th century the embankment was not surrounded on all four sides, and only two of the current building blocks existed, the one on the west and the other on the south, which

were separated by an incline. The southern block was topped by a tower with a dovecote, which was accessible via two archways on the roadway plane;

— important developments came about during the subsequent two centuries: two transverse buildings were added to the southern block, and on the other side, the southwest corner was still taken up by the incline, but now closed at its base by a small wall joining the southern and western building blocks;

— in the 14th C the two other corner buildings were erected, and the entire monastery complex was elevated by the addition of a storey. This raising and closing off of the hillock was likely the consequence of the events of the time, during which the Abbey found itself caught in the middle of the war between Pisa and Florence. It can therefore be assumed that the complex was first completed and then crowned with a crenellated wall to be able to carry out its new functional requirements as fortress and then only subsequently covered. Still today, the various constructional additions are visible on the facades, particularly on the western front, where the occluding stone wall is present at about the midpoint of the original building (analogous to the northern closing on the same front), and interrupted only at about two metres from the roadway plane, where the two masonry walls have been «embedded» into the original facade. Only traces of the furthermost southern building and its tower now remain;

— in the 15th century the cloister and the two transverse building blocks disappeared, in whose place only a garden or grove now remains: traces of the western building are evident on the church's southern flank, where cement vestiges trace the profile of a gable roof on its walls.

The first written document (Castiglia, 1998) from which it is possible to draw significant information on the morphological and functional state of the monastery, already transformed into an estate of the Military Order of the Knights of Saint Stephan, is an expense record:[3] one of the first entries, dated August 19, 1575,[4] attests to the need to demolish and reconstruct the walls «on the eastern part».[5] No reference is made to any barbicans or bastions, which historical studies instead indicate as having already been added (Testi Cristiani, 1987).

In a 17th-century architectural plan the complex encircles the terreplein of the embankment on the southern and western sides and the south-eastern corner, while the olive-grove surrounding the church on two sides up to the wall bordering the garden is sustained by a crenellated retaining wall that together with the building completes the four-sided structure topping the hillock (Severini , 1994–Sitte, 1992). The plan shows only one pentagonal cross-sectioned bastion[7], overlain by a similarly shaped room, perhaps an old look-out station of the fortified structure, which however has not survived to the present[8] There is no trace of the other bastions, whence doubts could be raised as to the dating of the document, which, if considered reliable, would be before 1682, the year in which the «the estate register» reports its construction: « . . . the grove boundaries have been restored, as they were in ruins in many places, and barbicans made»[9]

The cadastral survey performed by the engineer Pier Francesco Paoli in October, 1743 provides further information:[10] the northern view corroborates the integrity of the crenellated enclosure, but does not include the corner bastion, which was instead erected together with a second one behind the church apse (Barsanti D., 1992).[11]

A building plan compiled by the surveyor Giovanni Domenico Riccetti in 1776 instead indicates both the barbicans and the walls.

State of the art: surveying the structures' current state

A visual survey of the degree of cracking was carried out, during which any damage was recorded together with the most important features having potential effects on the structures' static equilibrium (Gucci et al. 1997). In particular, on the eastern façade we discovered rotation of the frontage wall in proximity to the S-E corner, insufficient mortar on the entire base portion of the masonry in the same corner, wide-spread cracking in the initial segment of the retaining wall near the tower, large, full-thickness fissures beneath the reinforcing chains, two nearly symmetrical diagonal cracks in the wall segment between the two barbicans, and vertical lesions in this same segment near the

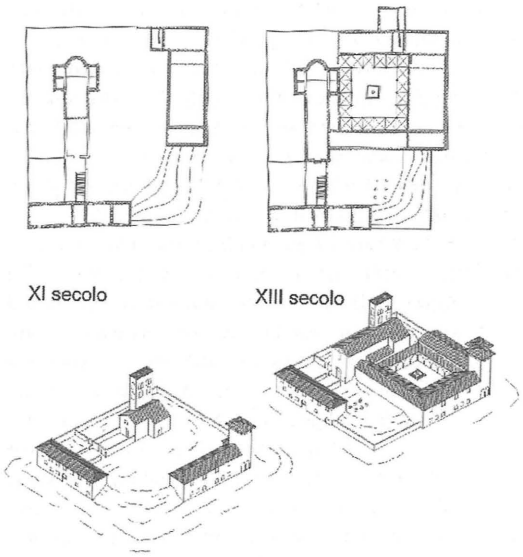


Fig.1
Historical views of the Badia S. Savino (XI–XIIX century)

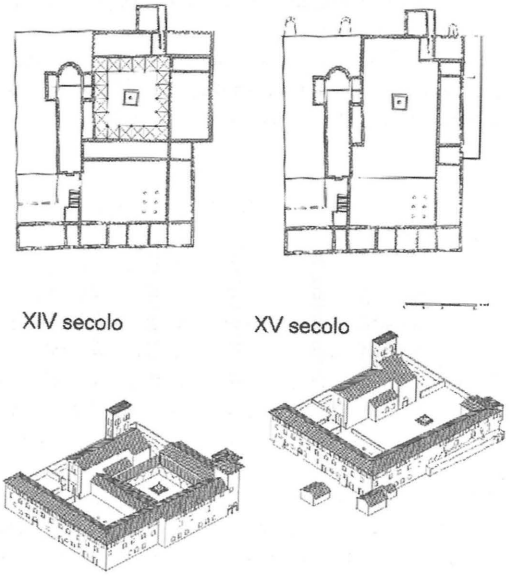


Fig.2
Historical views of the Badia S. Savino (XIV–XV century)

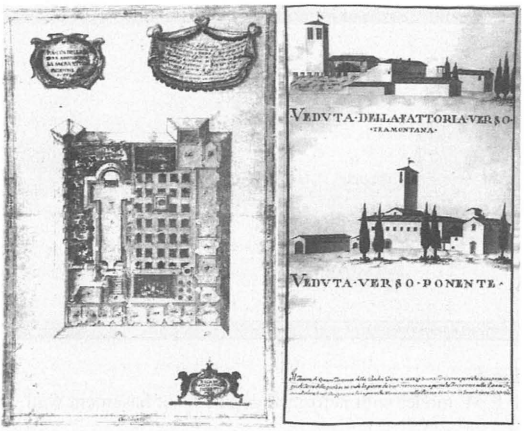


Fig.3
Drawing from P.F. Paoli manuscript (see footnote 9)

northern buttress, all of which are continually subjected to the mechanical action of the overgrowing vegetation.

The structure of the retaining walls of the Abbey's ground basement retaining walls has been simulated by means of an FEM code with 50 × 50 cm shell elements. From the mechanical point of view, the principal hypotheses were the following:

— Stress-strain law: in consideration of the aims of the analysis (to numerically verify the position of the existing cracks) and the uncertainties regarding the materials and loads, the material was considered to be elastic. Young's modulus was determined via the

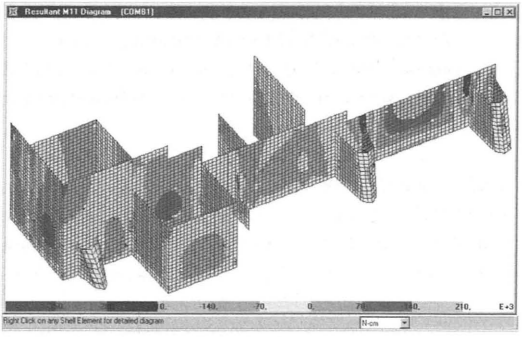


Fig.4
Finite element mesh of basament wall (M11 diagram)

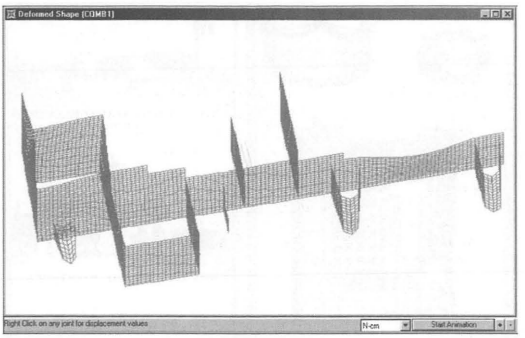


Fig.5
F.E.M. model with deformed geometry of basament wall

Hillsdorf pile-model. The masonry has been simulated as a series of regular layers of blocks and mortar of a given thickness (s_b, s_m) and elastic moduli (E_b, E_m) (ν_b, ν_m). Thus, the apparent Young's modulus is $E = Eb(1 + r) / (n + r)$, with $r = s_b / s_m$ and $n = E_b / E_m$. Several groups of masonry bonds have been distinguished, yielding six different types of walls.

— Restraints and supports: the masonry walls have been considered to be perfectly adherent to the ground, taking into account the progressive rising of the external ground level with respect to the original 11th-century Abbey nucleus, due to periodic flooding of the nearby Arno river, as demonstrated by the partially covered masonry arches on the southern façade of the basement.

— Horizontal ground load: two different geotechnical conditions have been examined for the ground behind the retaining walls: the absence of water (permanent load - drained case) and the presence of water (accidental load - undrained case).

By evaluating the stress diagrams, we have been able to arrive at a satisfactory correspondence between the critical cracked zone and the maximum tensile stress values (Mastrodicasa, 1943).

— the diagram of the bending moment acting in the horizontal direction (M_{11}) shows for the most part homogeneous values along the wall, except adjacent to the two northern barbicans: in this zone the effect of negative bending, as in a continuous beam near an intermediate support, produces strong tangential stresses and slops, while in the middle of the wall, the maximum positive normal stresses cause vertical cracking, as was corroborated by the survey of the Abbey's retaining walls;

— the diagram of the bending moment acting in the vertical direction (M_{22}) and the corresponding strained elastic configuration reveal a considerable loss of verticality in the central upper portion of the wall between the barbicans, as in a vertical cantilever beam loaded by the pressure of the earth. The cracks caused by this mechanism are not visible on the wall's free surface, but the combination of the two effects (M_{11} and M_{22}) produce characteristic symmetrical, upwardly concave, parabolic cracks, as in the present situation.

Given the peculiar results obtained in the northern portion of the support wall, the analysis regarding this section was extended: the panel between the barbicans acts as a plate fixed at its base and free at the summit, though partially bound on its lateral borders and subjected to a thrust orthogonal to its own plane. To better study this configuration's behaviour, the output stresses were rearranged using vertical wall sections on which to project the values yielded by the analysis.

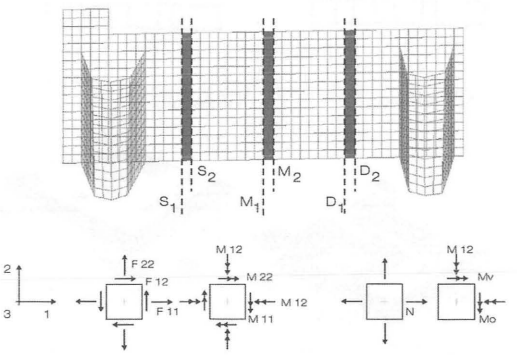


Fig.6
Vertical sections M, S and D between barbicans

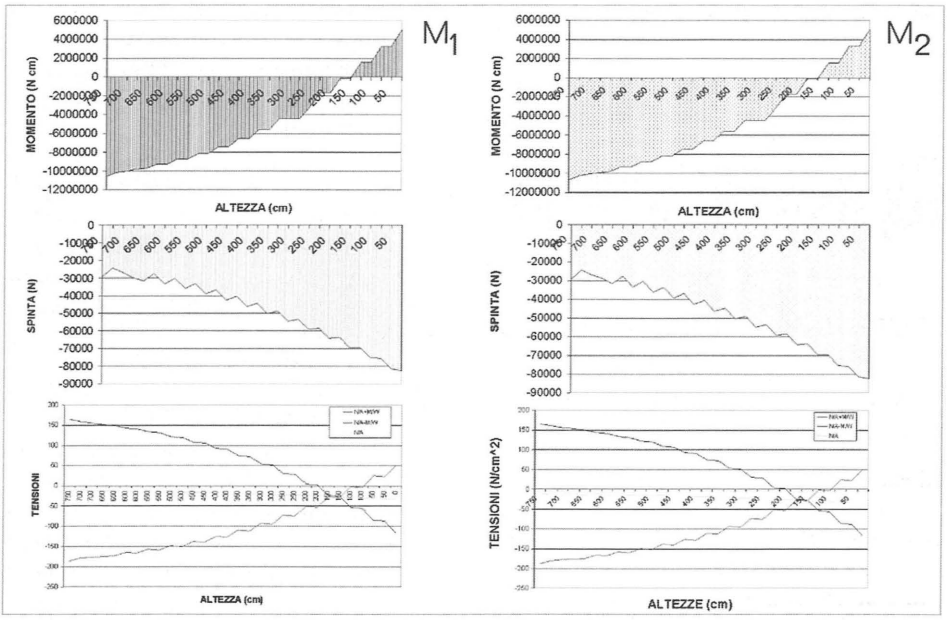


Fig.7
Bending moment, horizontal force and normal stress on section M1

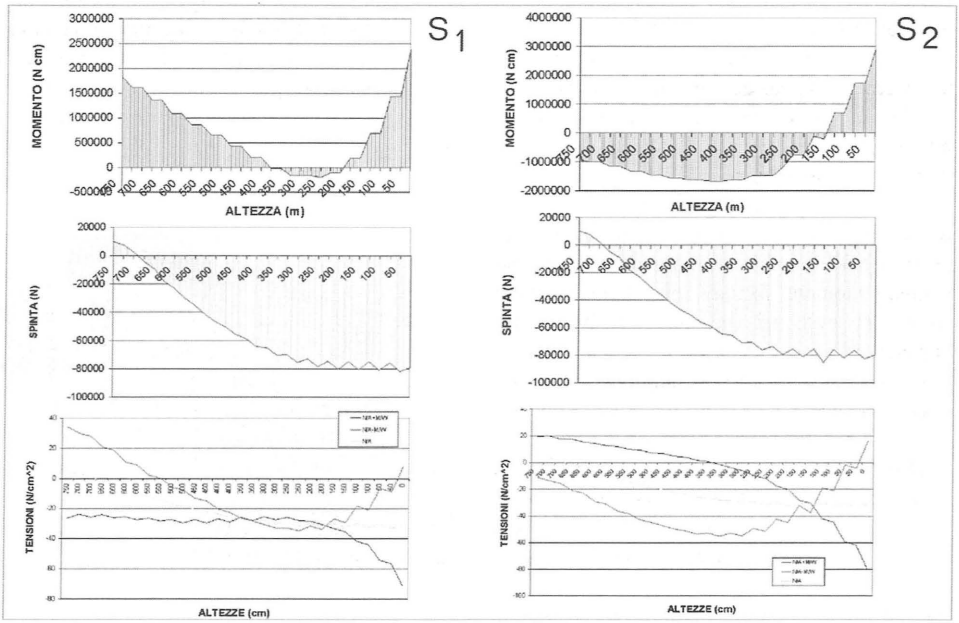


Fig.8
Bending moment, horizontal force and normal stress on section S1

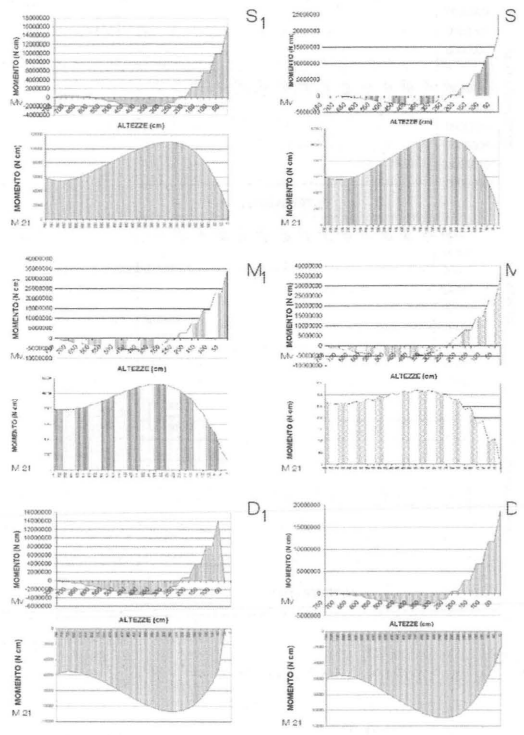


Fig.9
Bending moment and torque on sections M, S and D

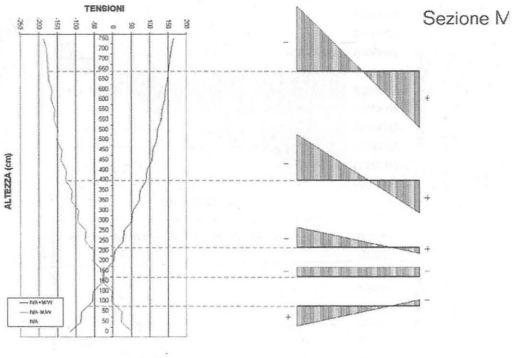


Fig.10
Vertical normal stress along section M

sections and stabilizes the wall against bending effects, which are in turn impeded by the stiffening against torsion offered by the barbicans. Ultimately, along horizontal sections the panel exhibits maximum bending in its upper portion where the stiffening effect of the barbicans is lower, while in the lower part, the greater thickness of the wall jointed with the axial stress leads to less bending, with consequently smaller tensions, resulting in a advantageous «arch effect» between the bases of the two barbicans.

— Examining the panel along vertical sections reveals that the torsional moment, M_{12} and the bending moment, M_{22} are related to the shear force, T_2 and, in the same fashion, the horizontal panel sections reveal a relation between M_{11} and M_{12} and the shear force T_2, both defined by the well-known equilibrium equation:

$$\partial M_{11} / \partial x_1 + \partial M_{12} / \partial x_2 = T_1;$$

$$\partial M_{12} / \partial x_1 + \partial M_{22} / \partial x_2 = T_2.$$

— To such actions we must add the contributions of the axial strain. Due to the wall's own weight, the axial strain acts along the horizontal

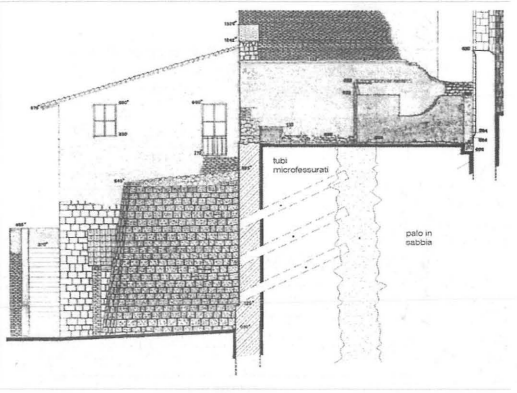


Fig. 11
Geotechnical reinforcement behind the basament wall

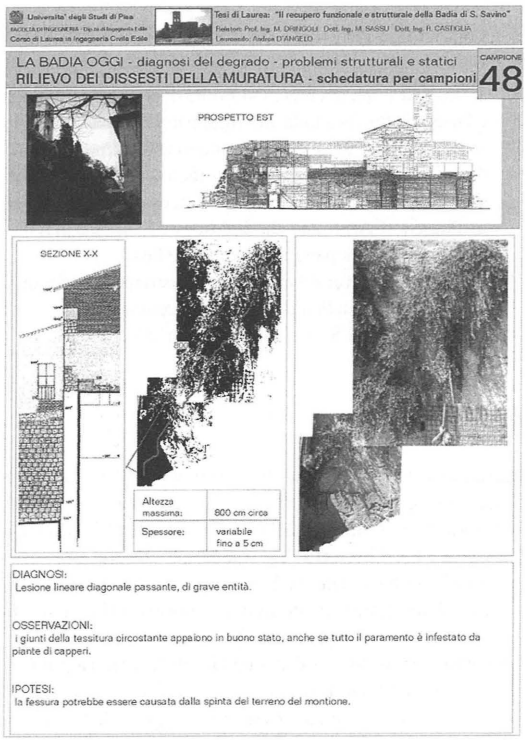


Fig.12
Typical schedule of structural survey

Conclusions

The combined historical and equilibrium analyses of the Abbey has furnished some interesting indications:

— it has helped to define the static behaviour of the building structures, revealing the arch effect operating in the wall's northern portion, where due to the presence of the bastions opposing orthogonal displacements, a thrust develops in the vicinity of the base and furnishes a bearing capacity entirely analogous to that of an arch.

— it has confirmed some of the assumptions regarding the different times at which various structural modifications were made and their effects on the static configuration. For instance, the structural role of the chains and the r.c. buttress are nearly irrelevant to the structure's overall behaviour, as they only act locally to re-establish equilibrium conditions, which the masonry would, according to the theoretical model (made up of elastic, homogeneous, intact material), reach on its own,.

— it has allowed proposing appropriate consolidation operations in order to enable the structure to satisfactorily perform its support function: the burden of the thrust from the undrained water in the bastion turns out to be a major factor in its instability. Thus, a first necessary operation (above and beyond repair of the wall in the degraded areas), will have to be the reopening of the old drain holes and the creation of new ones to assure good water outflow. Such operations may even be sufficient in the wall's southern portion, where sinking has substantially reduced the thrust of the ground. However, this is not the case in northern segment between the two barbicans, where the results of modelling, in addition to the alarming nature of the cracking already present, point to the need for further precautionary measures.

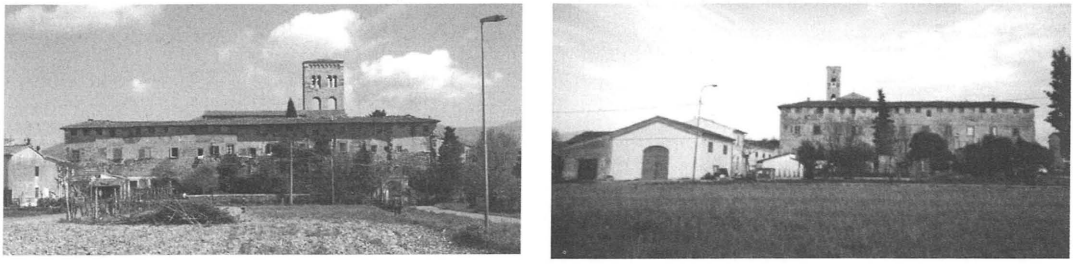


Fig.13
Views of the Badia S.Savino, Cascina (PI)

In conclusion, the first operation to be carried out is to restore the original load-bearing sections of the wall, without however modifying its historical bonds. The second stage then calls for increasing the embankment's ability to drain off rainwater, thereby substantially reducing the thrust acting on the retaining wall.

Notes

1. *Plan of Badia S. Savino della Sacra e Ill.ma Religione di S. Stefano*, (Public Historic Archive of Pisa) ASPI, Ordine di S. Stefano, Piante e Disegni, 18, fig. 3.13.
2. A graphical hypothesis of the Abbey's historical evolution that we have followed in the present work is presented in «Piano di Recupero della Badia di S. Savino» («Plan for Recovery of the Abbey of S. Savino»), drawn up by the Cascina Township in 1996. The precise heading of the work is *Comune di Cascina, Hypothesys of historic evolution of Badia di S. Savino. Survey and schemes by: Bracaloni Cristiana, Turini Davide, Turini Sandra (degree dissertation, Aprile 1996)*, in Studio Architetti Associati M. Ciampa P. Lazzeroni, *Piano di . . .* , op. cit.
3. «Book of Badia di S. Savino manuscripted by prior Domenico di Brando da Greve, fattore, started on 31 March 1572». ASPi, Ordine di S. Stefano.
4. ASPi, Ordine di S. Stefano, S 2828.
5. Actually, the statements are interrupted because of tears and missing or illegible parts in the documents. For the presence of the bastion see F. Redi, *Edilizia medievale e organizzazione del territorio*, Pisa 1984, p.123.
6. «Plan of Badia di S. Savino della Sacra e Ill.ma Religione di S. Stefano», ASPi, Ordine di S. Stefano, Plans and Drawings, 18: is a 71.60 × 45.90 cm china-ink and watercolour paper manuscript, in a graphic scale of 5 Florentine arm lengths (2.91813) = 13.40 cm.
7. The pentagonal section is illustrated as mostly regular, contrary to that present today, which though still pentagonal, has been built up in the direction orthogonal to the walls.
8. ASPi, Ordine di S. Stefano, M 714, c. 95 v.
9. «Plans of the farm properties of Badia di S. Savino della Sacra e Ill.ma Religione di S. Stefano», P. F. Paoli 1743, ASPi, the document «Ordine di S. Stefano, Piante e Disegni, 46»: is a hide and rigid parchment manuscript (84.15 cm × 61.00 cm) containing China ink and watercolour sketches, which include 17 plates of various sizes: 7 plans of the «Seidici» estate, the lands at Piaggia d'Arno and the holdings of the San Savino estate, as well as panoramas of these last.
10. There are however 8 battlements illustrated therein, one less than those indicated in the 17th-century plan.
11. ASPi, Ordine di S. Stefano, piante, n. 53.

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Investigations for the knowledge of multi-leaf stone masonry walls

Francesca da Porto
Maria Rosa Valluzzi
Claudio Modena

The use of stone masonry is very common in many historic constructions, both architectural monuments and whole urban centers. Such architectonical heritage is often located in areas characterized by a medium-high seismic hazard and frequently reveals mechanical damage due to the constructive peculiarities of masonry. It is characterized by scarce or no connection through the thickness and by a possible substantial presence of voids, being consequently affected by brittle collapse mechanisms. In order to understand the mechanical behavior of such masonry, to properly analyze it, to design the most suitable conservation strategies and the most effective consolidation interventions, it ought to start from a clear description of its typological and morphological characteristics.

Some different available walls classifications were used for this purpose, together with detailed data-bases, aimed to specific analyses. In particular, an existing extensive data-base was enriched with the analysis of other almost 100 walls sections. It was thus identified a wall «model» sufficiently representative of the existing typologies.

On the basis of those preliminary information, a comprehensive experimental research has been recently performed at the University of Padua. Seventeen physical models were built and tested with destructive and non-destructive techniques, before and after the application of different consolidation techniques. Results confirmed that grout injection is the most effective consolidation technique for this kind of masonry.

Some of the goals scored by the performed research and discussed in the present papers are: (i) the clarification of the current classifications of stone walls to identify some typical walls typologies; (ii) the design and the validation of a physical model sufficiently representative for laboratory researches. Finally, the use of non-destructive techniques (in particular, sonic waves and tomography), for a non-invasive evaluation of the conditions of stone walls, in order to have useful information for a proper design and control of the intervention, is discussed.

Introduction

The local and global behavior of masonry walls is affected by the type and quality of materials, the presence of connections through the leaves, the shape and dimension of the elements, the thickness of mortar joints and the constructive techniques (Binda et al 1999). The quality of masonry also depends on the workmanship of the constructors. In the case of «noble» buildings such as the gothic cathedrals, in fact, the constructive techniques were developed and their knowledge was handed down from father to son. Conversely, the so called «minor constructions» that constitute urban centers and rural dwellings, were seldom built in a workmanlike manner (Antonucci 1997). These elements that characterize masonry behavior are not easy to identify. In fact, the materials, the technique and the process of construction, in the

case of multi-leaf stone masonry walls in particular, are dominated by uncertainties and irregularities.

Nevertheless, the knowledge of each masonry typology features can help in the choice of theoretical and physical models for analysis and experimental study of masonry. Similarly, the knowledge of features and typical faults can guide the choice of proper and effective repair interventions (Binda 2000). Therefore, the deep knowledge of the different stone masonry typologies is of basic importance and is necessary not only for historical and documental purpose, but also for scientific-technical research.

The morphological and typological characterization of multi-leaf stone masonry walls can be carried out by comparison with the available classifications of masonry. On the other hand, experimental tools such as on-site inspection of the sections, measurements, non destructive tests (sonic tests, thermographies, radar inspections, etc.) can be used. Minor destructive tests on masonry (single and double flat-jack, etc.) and laboratory tests on sample taken from the walls, finally, allow evaluating the mechanical characteristics of masonry and characterizing the materials, for a more accurate description of the walls.

To properly lay out the research on the effectiveness of various strengthening techniques for stone masonry walls, the available classifications of masonry were accurately studied. Due to the large variety of existing typologies and to the different approaches in their study, different kinds of cataloguing were found. Using information collected from data-bases and other literature sources, the most frequent stone walls typology and its characteristics were found. Only after these premises a physical model was designed and constructed, in order to create laboratory specimens representative of real conditions. Non destructive tests (sonic tests and tomographies) were also performed, and their reliability in evaluating masonry walls' morphology and conditions was checked.

Available classifications for stone masonry

As above mentioned, different classifications of masonry typologies can be found in literature. Three main groups of classifications were identified by the authors and were respectively named systematic, methodological and analytical, according to their aims, structure and results. A brief description, for each of them, is given in the following.

Systematic classifications of masonry walls

Systematic classifications are those that follow a fixed and strict order, subdividing masonry in several subcategories by specifying for each class more and more detailed characteristics. A typical cataloguing of this kind is often based on the characteristics of the elements that constitute masonry (stone, brick, adobe, etc.) and is generally adopted in handbooks of restoration. The classification given by De Cesaris (1996) is, in the authors' opinion, an example of systematic cataloguing. De Cesaris classifies stone masonry according to the shape of the elements (ashlars, roughly shaped stones, pebbles), to their assembly on the external leaves and through the section and to the presence of other materials (mortar, brick courses, wooden frames, etc).

In the case of stone masonry, due to the several different types, shapes and working processes of the elements, the classification of a wall according to these criteria is not always univocal. Very often, various classifications for the same wall are possible with reference to different parameters, such as the texture of the external leaves or the composition of the sections. The medieval town walls of Cittadella nearby Padua, Figure 1, are an example of this kind. They are a mixed kind of stone masonry, both for the characteristics of the external leaves and of the section (Figure 2 and Figure 3).



Figure 1
Example of cyclopean walls: overall view of the town walls of Cittadella (Padova), built in 1220

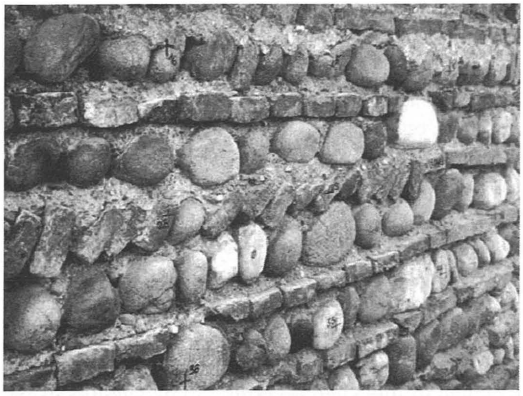


Figure 2
Detail of the town walls of Cittadella. From the external leaves, the wall can be classified as «stone masonry with brick courses» or «mixed masonry». They are made of pebbles and mortar with horizontal courses of bricks



Figure 3
Detail of a niche excavated inside the town walls of Cittadella. The internal leaf is different from the external ones. It is an «opus concretum», made of regular alternate layers of pebbles with brick pieces and thick mortar beds

Methodological classifications and development of mechanical models

Methodological classifications, on the contrary, are not based on groups of rules that allow cataloguing masonry by describing it. These classifications are more related to functional aspects of masonry than to its appearance; therefore masonry is not described and catalogued on the bases of physical, objective aspects, but analyzed with reference to constructive or mechanical principles. Giuffré (1991), for example, subdivides masonry walls into systems characterized by similar behavior. The development of mechanical models for masonry behavior is thus implicit in his classification. A first distinction between «cyclopean» masonry, such as that which constitutes the defensive system of medieval towns (see Figure 1), and masonry used for normal buildings, is made. In fact, even if very often the constructive techniques are similar, dimensions, ratio of dead to live loads and structural behavior are different.

In the case of normal buildings, two large classes of masonry are those corresponding to a popular and a noble tradition of building construction. Multi-leaf masonry walls, made of pebbles and irregular stones, belong to the class of «minor» constructions. Concrete masonry walls, made of a casting of stone elements bound together by mortar, like in the Roman «opus concretum», represent a development of popular construction techniques. Masonry made of well layered regular blocks, with elements perpendicular to the width of the wall that interconnect the different wythes, is typical of «noble» buildings.

Concrete and regular block masonry, to a certain extent, are characterized by similar collapse mechanisms. Concrete masonry, in fact, has a monolithic section that allows the redistribution of vertical loads and develops an overturning resistance under out of plane loads. The presence of interconnecting elements through the leaves of stone masonry walls makes the section act in a similar way. Furthermore, the presence of good connection among perpendicular walls, allows the transfer of horizontal loads from out-of-plane to in-plane loaded walls, which can develop higher strength (Giuffré 1991).

Conversely, multi-leaf stone masonry with scarce connections through the leaves and irregular texture of the section is characterized by instability under vertical loads due to the slenderness of the leaves, and

by local crushing phenomena and detachment of the external leaves, due to the non-homogeneous distribution of loads (Giuffré 1993). Under out-of-plane actions, the absence of interconnection among leaves facilitates the development of independent kinematic mechanisms for each wythe and the expulsion of the external leaves (Figure 4). In this case, the out-of-plane collapse, with local or global overturning of masonry (Figure 5), happens for values of applied loads lower than those necessary on monolithic walls (Giuffré 1991).



Figure 4
Expulsion of the external leaf of a stone masonry wall after the Umbria-Marche earthquake (Italy, 1997)



Figure 5
Global overturning of a stone masonry wall after the Umbria-Marche earthquake (Italy, 1997)

Analytical classifications and development of masonry data-bases

Finally, analytical classifications are again based on ordering, on a descriptive base, the different masonry typologies, unlike methodological classifications, but they go from detail to general categories through the experimental and accurate analysis of representative masonry samples, unlike systematic classifications. Different characteristics of masonry are interlinked in order to reach a level of synthesis, where the single walls analyzed form themselves into groups distinguished by typical common features. An example of this kind, according to the authors, is the catalogue made by a group of researchers at the Politecnico of Milan, described in the following. More than 250 stone wall sections, found in different Italian Regions (Lombardia, Trentino, Friuli, Veneto, Liguria, Emilia Romagna, Abruzzo, Marche, Toscana, Umbria, Basilicata e Sicilia), were classified by defining the characteristics of four basic parameters. These parameters are: (i) the kind of stone element, (ii) the assembly of the elements, (iii) the wall section, characterized by the presence of one, two or three leaves (Figure 6), and (iv) the mortar used. On the bases of the information collected, five classes and eight typologies of stone masonry were identified (Binda 2000).

Besides classifying the stone masonry typologies, this cataloguing also creates a data-base of information on stone masonry. In order to collect homogeneous and comparable data, the walls were

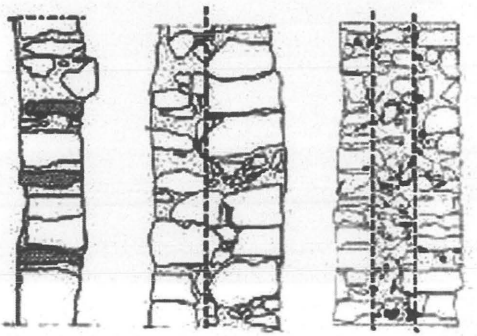


Figure 6
Typical stone masonry sections: one, two, three leaves. From Binda et al. (1999)

analyzed following a procedure whose general structure is fixed in a form (Binda 2000). Not only the morphological characteristics of masonry, but also results of mineralogical, petrografic, chemical, physical and mechanical analyses on stones and mortars, plus mechanical and sonic tests results on masonry, are collected in these forms. If the analyzed wall is then consolidated, tests on masonry can be repeated before and after intervention. Also tests on the repair materials (such as tests on injection grouts) can be performed. This allows differentiating stone masonry typologies not only for the morphological characteristics, but also on the basis of mechanical parameters, giving possible information on the effectiveness of the interventions.

Problems related to stone masonry walls classification

The classification of stone masonry, due to its intrinsic complexity, deserves particular attention. For example, three-leaf stone masonry walls are generally called «a sacco». This name, which is usually misused, should define a particular type of three-leaf masonry walls, whose internal leaf is generally thicker than the external ones. In reality, three-leaf stone masonry walls are characterized by different construction methods that gradually changes from the actual «a sacco» walls, made with a completely loose internal core held by two separate external leaves, to the fixed concrete core masonry typical of the Roman age. In the first case the poor internal core, characterized by the presence of diffused voids, exerts a thrust on the external leaves. Friction is the prevalent resistant mechanism, while cohesion within the internal leaf and adhesion between the leaves is scarce. Complex crack patterns, detachment and expulsion of the external leaves characterize the collapse. In the case of concrete core masonry, the internal leaf is characterized by high cohesion, good mechanical properties and an actual load bearing capacity. The external leaves work as formwork for the concrete core casting and there is good adhesion between them and the internal leaf. Moreover, the wall sections are characterized by a monolithic behavior (Doglioni and Parenti 1994).

These walls typologies, which differ for construction techniques and mechanical behavior, are in general characterized by thick sections. For ordinary buildings, with load bearing walls 50–70 cm thick, the most common kind of multi-leaf section is built with an ill-shaped core, which is not cast but layered more or less accurately by the bricklayers. In such a context, different values of cohesion within the internal leaf and of adhesion between the leaves, possible presence of transverse elements, different percentages of voids, can leads to relevant differences in the walls (Doglioni and Parenti 1994).

Identification of a typical wall typology

Typological characterization

From the available data, the most frequent stone masonry typology is made of two or three leaves not interconnected, with the external leaves made of roughly shaped stones bonded in sub-horizontal courses. The average thickness is about 50 cm with a ratio of thickness between the external and the internal leaves of about 1:0.5. The highest frequency of voids percentage on masonry sections is distributed around two groups of values: from 1.13 to 3.8% and from 11.05 to 14.04 (Binda et al. 1999).

Also at a national scale it is stressed that one-leaf stone masonry is definitely rare (a part from Sicily, percentages of one-leaf stone masonry in different regions of Italy vary between 0 and 8%). Regarding the composition of masonry, stone constitutes at least 60% of the section, and average values are around 68.8%. Mortar constitutes 11 to 37% of the section, while voids are in general more than 2% (Binda et al. 1999). Other almost 100 multi-leaf stone wall sections described in literature were analyzed by the authors (da Porto 2000). Both existing walls and laboratory specimens were considered. Table 1 synthesizes the results found on three-leaf stone walls.

Both limestone and sandstone are common in existing constructions. The maximum dimension of limestone elements varies from about 15 to about 60 cm, and is in average equal to 30 cm. Dimension of sandstone elements varies from about 15 to about 25 cm. Average compressive strength for limestone is about 80 MPa, for sandstone is about 100 MPa. Most of the mortars are made of air-hardening lime. The consistence of existing mortars is, in general,

Table 1. Total thickness, ratio between the thickness of external and internal leaves and percentage composition of three-leaf stone masonry, measured on laboratory specimens and on existing walls

Wall section	Thickness		% composition		
	total (cm)	ext:int	stone	mortar	voids
Av. values physical models	40	1:1	—	—	12÷13,75
Av. values existing walls	53	1:0.55	67.87	28.39	3,74
Max values existing walls	66	1:0.78	84.5	36.46	11,05
Min values existing walls	36	1:0.4	55.61	12.6	0,38
Proposed values	50	1:0.78	68	22÷17	10÷15

powdery, with compressive strength between 1.2 and 8.7 MPa. The dimension of joints is irregular, due to the use of natural stone, and in average varies between 1 and 4 cm.

Mechanical characterization

Regarding typical mechanical parameters, an extensive study on values of strength and elastic moduli for multi-leaf stone walls was carried out. Data collected by nine research groups in Italy, Slovenia (Tomaževič 1992), Greece (Vintzileou and Tassios 1995), Belgium (Toumbakari et al. 2000) and Germany (Egermann 1993) were analyzed. Also researches performed in Canada, Egypt and other European countries were taken into account (da Porto 2000). Table 2 shows typical values of compressive strength, elastic modulus and shear strength for multi-leaf walls, before and after consolidation with grout injection.

Experimental procedures for the study of three-leaf stone masonry walls

Design and construction of the physical models

The design of stone masonry specimens, to be tested before and after consolidation with different strengthening techniques, was based on the collected information. A three-leaf section was proposed. The specimens were designed 50 cm thick, equal to the average value found. The width of the walls was

Table 2. Average, maximum and minimum values of mechanical parameters for multi-leaf stone masonry, measured on laboratory specimens and on exiting walls on site, before and after grout injection

Multi-leaf stone masonry	Compressive strength (MPa)		Elastic modulus (MPa)		Shear strength (MPa)	
	original	injected	original	injected	original	injected
ZAG Ljubljana (lab. specimen)	0,635	1,57	293,5	1784,5	0,06	0,304
NTUA Athens (lab. specimen)	1,742	3,725	5073,8	7863,8	—	—
KU Leuven (lab. specimen)	2,354	3,367	4791,8	3466,7	0,349	0,65
Average on site values	1,113	1,408	367,8	756,4	0,134	0,108
Maximum on site values	2,243	1,596	1287,9	3012	0,227	0,237
Minimum on site values	0,639	1,37	166,8	351,7	0,029	0,049

chosen equal to 80 cm, that is to say, about three times the maximum dimension of the stone units (25 cm), while height was chosen equal to 140 cm, about twice the width. These dimensions were chosen to avoid scale and edge effects, in order to have uniformly distributed compressive stresses in the central area of the specimens under uniaxial compression loads, according to Gelmi et al. (1993). The external leaves were designed 18 cm thick and the resulting inner leaf was thus 14 cm thick. This thickness ratio 1:0.78, besides reproducing a typical ratio collected in the north-eastern part of Italy, is the average between the values detected in literature among existing walls (1:0.55) and laboratory specimens (1:1). With the same criteria, a proportion of 68% of stones, 22–17% of mortar and 10–15% of voids, on the volume of the whole wall, was considered typical for three-leaf stone walls (da Porto 2000). Figure 7 shows the designed specimens.

The specimens were built as a whole wall 13.60 m long by three experienced bricklayers (Figure 8). The long panel was cut into 17 parts with a wire saw, after 3 weeks curing. For the handling and the load distribution during the laboratory tests, two concrete beams, 20 cm high each, were built on the bottom and on the top of the specimens. The external leaves of the walls were made of rough-shaped limestone blocks, bonded in sub-horizontal courses, with mortar joints 1 to 4 cm thick. The internal core was built with mortar and limestone scabblings, derived from the rough-shaping of the stones, poured into not compacted layers between the two external leaves, so that a certain amount of voids was created. To reproduce the worst wall conditions, no transversal connection was provided through the leaves.

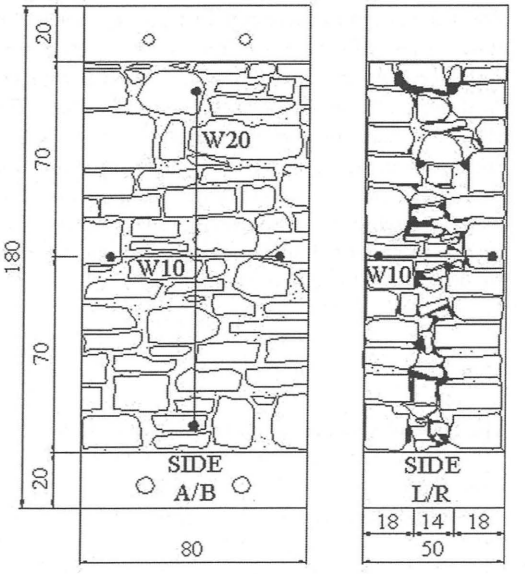


Figure 7
Geometry of the walls and position of the transducers during the compression tests

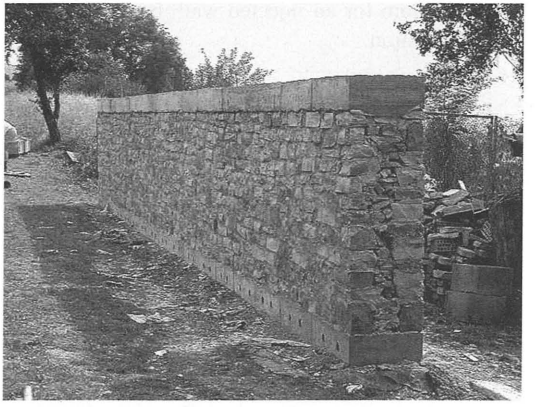


Figure 8
View of the entire wall built, before the wire-sawing

The material used for the construction combined the requirements of reproducing historical walls conditions (e.g. chemical and mechanical characteristics of mortar, composition of the internal core, etc.) and of using local and easy-to-find materials. The limestone was from the Cugnano quarry, located in the north-eastern part of Italy. The mortar was composed by a binder of natural hydraulic lime and lime putty (ratio 1:3); lime/sand ratio was equal to 1:3, water/lime ratio was 0.5 (ratios in volume) (da Porto 2000).

Experimental program

Nine walls were tested under uniaxial compression after 28 days of curing. Eight of these specimens plus the

remaining eight were repaired with different strengthening techniques: injection of two different grouts, repointing, transverse tying, and their combinations. All the specimens were then re-tested about 60 days after construction, about 28 days after the execution of interventions. The intervention techniques are described in Valluzzi, da Porto and Modena (2001).

Tests were performed under force control at a load increment rate approximately equal to 0.25 kN/s. Six displacement transducers were applied to the specimens: four on the main façades of the wall, to register vertical and horizontal displacements, two on the transverse sections. Tests were performed with two loading cycles. Figure 9 shows a typical stress-strain diagram for an injected wall, before and after the intervention.

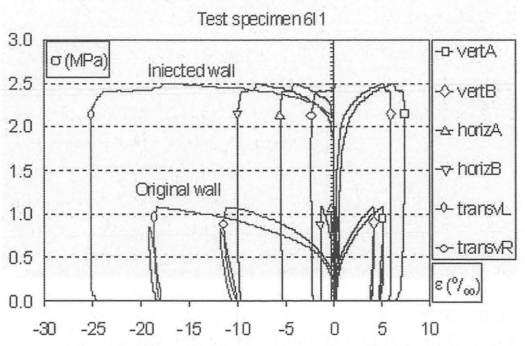


Figure 9
Stress-strain diagram (wall 6I1), before and after grout injections

Some of the walls were also subjected to sonic tests. These tests consist in generating an elastic wave by means of an instrumented hammer and registering the same wave in another position on the wall with a piezoelectric accelerometer. From the knowledge of the sonic pulse velocity, it is possible to draw some information about the current conditions of masonry. Different kinds of sonic wave transmission were used: direct transmission through the wall thickness, indirect transmission on the same walls surface, sonic tomographies, with measurements of sonic pulse velocities along different ray-paths on the same wall section.

Validation of the model

The compressive strength of stone, measured on cubes (71 mm for each side), was approximately of 164 MPa. Samples of mortar (40x40x160 mm prisms) were taken during the constructions of walls, and tested after 28 and 60 days. Their compressive strength was equal to 1.57 and 1.64 MPa, respectively. Thanks to the wire-sawing, the masonry panels were characterized by plane, easy to survey, transversal sections. The design assumptions, as regards the proportion of stones, mortar and voids were thus checked and confirmed.

Before the interventions, the maximum strength of the tested walls varied between 0.99 and 1.97 MPa; however, evident cracks patterns already started at a stress level varying from 0.55 to 1.09 MPa. The average value of the secant modulus of elasticity (calculated between the 30% and the 60% of the maximum strength) was of about 1700 MPa. The cracks had a vertical or sub-vertical trend, as expected for failure under compression, and most of them were located in the transversal sections, between the different leaves. The collapse thus occurred by detachment of the layers and out-of-plane expulsions.

In the walls repaired by means of grout injections, a quantity of grout corresponding to a percentage of about 14% of voids on the wall volume was introduced. After grouting, the average value of the maximum strength increased of 40% (about 2.5 MPa). Regarding the modulus of elasticity, it increased, in average, of about 35%, reaching the average value of 2347 MPa. Conversely, the transverse tying of walls strongly reduced transversal strains, of about the 50% at peak stress and of about the 90% at the same stress level.

Sonic tests

The original specimens showed values of sonic pulse velocities varying, in general, from 1500 to 400 m/s, which correspond to conditions of masonry from fair good to very bad (Berra et al. 1992). The lower part of the walls was characterized by higher values, corresponding to good conditions (Figure 10a). This reflected the construction process of the specimens, during which only the lower part of the internal leaf was compacted by the bricklayers. The lowest values

of sonic pulse velocity were actually found on the inner loose leaf of the walls.

After the compression tests, a general decrease of sonic pulse velocities was detected. On the contrary, after grouting, the pulse velocities were about 3000 m/s, showing increments of even 1000%. During the injections, the quantity of injected grout and its propagation inside the walls was checked. It came out that the highest quantity of grout was injected where the previous lowest values and the subsequent highest increments of sonic pulse velocities were measured (Figure 10b).

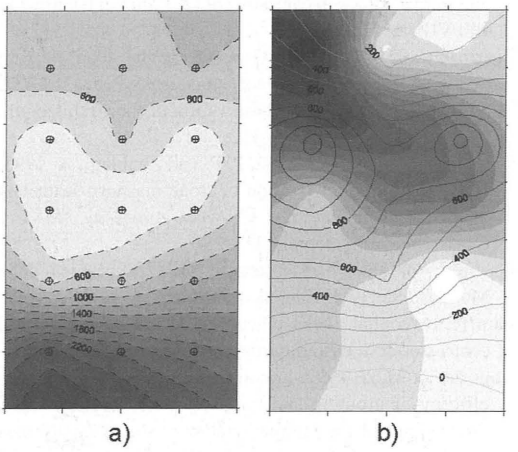


Figure 10
Vertical sonic tomography on the internal leaf of a wall after compressive tests (a). Quantity of injected grout on the same wall (background colours) and sonic velocity percentage increase after injection (foreground lines) (b). The darker colours stand for higher sonic pulse velocities (a) and for higher quantity of injected grout and higher velocity increases (b)

Conclusive remarks

The experimental simulation of the behavior of three-leaf stone masonry walls involves problems related to typology identification, materials, consolidation and diagnosis techniques. In the present contribution, the preliminary effort to define typological features and values of morphological and mechanical characteristics for stone masonry walls was described.

The various classifications of stone masonry walls found in literature differed for aims and structure. In general, it can be said that systematic classifications illustrate very well the morphological features of masonry. Due to their anthological and descriptive nature, they have a great historical and documental significance. Methodological classifications do not catalogue the characteristics of the different masonry typologies. However, they are very useful for an interpretative view of masonry. For example, the cataloguing of this kind here presented allows a qualitative evaluation of the mechanical behavior and the collapse mechanisms of walls. Finally, analytical classifications lend themselves to create data-bases of practical information, for operating on stone masonry walls. The simultaneous use of all of these classifications add complementary information to the knowledge of masonry typology, structure, behavior, and can avoid interpretative errors as those regarding the so called «a sacco» walls.

The accurate preliminary study of stone masonry walls led to the choice of materials, morphology and constructive techniques representative of existing walls. The compressive strength of the stone and mortar used was similar to those measured on real walls. Also the compressive strength of the masonry specimens showed an excellent fit with the results obtained on existing walls. The experimental values of the laboratory specimens, in fact, were all between the minimum and the maximum value measured on site. The modulus of elasticity measured on the specimens was higher than the real values (+30%, in average). However, a perfect fit between elastic moduli of real walls and physical models is not easy to obtain, as was found in literature. The use of lime based mortars, characterized by low compressive strength and modulus of elasticity if compared to cement mortars, limits the errors and allows reproducing the real conditions of historic masonry.

Also after the repairs it was possible to check the validity of the physical models built. The percentage increase of compressive strength for the injected walls was similar to that obtained on real walls. Also the final values of stiffness were still compatible with the elastic characteristics of existing stone masonry walls strengthened by injection. Very high increases of strength and stiffness found in literature, are related to laboratory research on three-leaf stone masonry specimens built with 1:1 thickness ratio

between the external and the internal leaves. This proportion amplifies the effect of injection, but it is not typical of existing wall sections, according to the available data.

The original values of transverse strain and the restraint action carried out by the ties, in the specimens strengthened by means of transversal tying, confirm that collapse, in the physical models, occurs by detachment of the layers and out-of-plane expulsions. Therefore, not only the mechanical parameters, but also the observed collapse mechanisms demonstrate the validity of the physical models built. It is worth stressing that only a preliminary accurate study of existing walls and a proper design of the physical models allow the achievement of good results, that is to say the design and construction of laboratory specimens that are actually representative of existing walls.

Finally, the sonic test results well reflected the original poor condition, the damaged condition and the good conditions after consolidation of the specimens. It was also demonstrated the effectiveness and reliability of sonic tests in individuating areas characterized by the presence of voids and by lower density, and in detecting the change in masonry walls' conditions and consistency. Even if this kind of tests still need to be improved and calibrated with the mechanical parameters of masonry, it seems to be a useful and promising tool for a completely non-destructive evaluation of masonry conditions.

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The builders of Roman Ostia: Organisation, status and society

Janet DeLaine

Direct documentary evidence for the organisation of the ancient Roman construction industry, and for the social and economic status of builders and their place in society, is very limited compared with what is available for the Renaissance and later periods (DeLaine 2000b, 120–21). Together with occasional and entirely incidental mentions in literary sources, there is a small body of legal precepts relating to building contracts (Martin 1989), and a slightly more substantial corpus of inscriptions relating to individuals engaged in the construction industry. Many of the latter are funerary epitaphs, but they also include documents relating to the *collegium* of the *fabri tignuarii* (the association of builders), which give lists of names of members or are dedications to or by the main magistrates of the *collegium*. Attention has largely focused on the evidence from the city of Rome (e.g. Anderson 1997), but the study has been hampered by the difficulty we have in associating the *collegium* and its members with any specific projects. Even in the high imperial period, discussion is inevitably reduced to generalisations, as only the quite exceptional building projects of the emperors are at all well-preserved, while the documentary sources are too fragmentary to say anything useful about the social structure of the *collegium*.

At Ostia however the data is much more self-contained. This is partly due to the rebuilding of most of the city during the course of the second century AD (Figure 1),[1] using a distinctive technique of rubble concrete faced with brick or brick and reticulate. For much of this it is possible to determine remarkably precise construction dates, based on the use of bricks stamped with a date which is most likely the year of their manufacture (Bloch 1953, Steinby 1974–75). The resulting micro-chronology allows us to think of these building projects as events in real time originating in individual human actions and choices, most evident in the details of construction and the materials employed. In addition the epigraphic evidence relates to a much smaller overall population and in this the *fabri tignarii* are proportionally much better represented than in Rome. This paper is a first attempt to combine these two bodies of evidence,

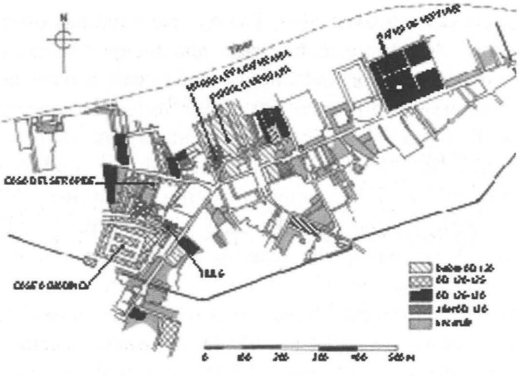


Figure 1
Ostia, areas of new construction c. AD 110–140 (J. DeLaine, P. Rose).

using this well-documented and closely dated body of constructional practice to flesh out the epigraphic record of the individual builders themselves over the second century AD.

The nature of construction

The key to isolating individual building practices is the sheer quantity of structures built in concrete which survive at Ostia from this period, and the range of variation of detail possible within this sophisticated constructional system. The same basic materials and techniques were applied in a wide variety of different ways, and while some of the differences are chronological, many are clearly contemporary. Although some of the variety can be explained by structural and/or economic requirements, or by architectural and aesthetic considerations, part appears to be due to the individual builders, their level of skill and their particular ways of working. Careful consideration of these details therefore throws much light on the organisation of the building industry.

The variety of structural choices can be seen most clearly in the multi-storey residential and commercial *insulae* built of brick- and reticulate-faced concrete which form the majority of the urban fabric. In these, brick facing was often used selectively, at openings and corners where good straight edges were required, and at points of stress such as at the intersection of walls, while the rest was of reticulate (Figure 2). For extra reinforcement, some buildings had travertine blocks inserted in vulnerable doorways or on the street corners of *insulae*. These same buildings often show differences in materials and facing technique between exterior and interior walls, which have no structural significance but rather reflect a concern with balancing economics and status display. Generally, a less expensive technique was employed for interior walls compared with exterior ones, for example in the *Casette Tipo* (III.xii-xiii, c. AD 100–110)[2] where the exterior is reticulate but the inside a coarse form of rubble concrete (DeLaine 2000a). Similarly, buildings in brick-and-reticulate often have the street façades just in brick, generally more carefully selected for colour and with narrower mortar joints than those of the interior walls, reflecting a greater investment in manpower and materials. Major entrances were often marked by the finest brickwork, with joints as small as a millimetre, and treated as miniature temple fronts exploiting the inherent polychromy of the material and sometimes with the finer details such as capitals and bases made out of white travertine for a distinctive decorative effect (cf. Kammerer-Grothaus 1974) (Figure 3).



Figure 2
Ostia, brick- and reticulate-faced concrete construction (V.iv.2), early second century AD

By comparing the structural and decorative detail in these residential and commercial buildings it is possible to detect the hands of several different groups of builders at work, while brickstamps provide information on their sources of building materials which can point to different contractors or clients (DeLaine 2002). The *Case a Giardino* (III.ix) and the



Figure 3
Ostia, Insula dei Dipinti (I.iv.2–4, c. AD 130–138), west façade in carefully selected yellow brick with red brick detail at entrances

Caseggiato del Serapide (III.x.3), two residential complexes of roughly the same date (c. AD 124–126), show this clearly. The *Case a Giardino* have outer walls of a uniform, salmon-red brick and a distinctive string course of projecting brick running along the main street façades (Figure 4). The major entrances are framed by engaged columns or pilasters in fine brickwork and have travertine insets in the door frames and travertine supports for the wide flat door arches. The interior walls are of brick and reticulate, although the brick here is more mixed than on the façade, and where façade joins with interior brickwork the two meet in single alternating courses. The brick comes from a number of producers, with just three accounting for over 50% of the total. The nearby *Caseggiato del Serapide* is built entirely of uniform golden yellow to brown brick with a total absence of reticulate and no use of travertine (Figure 5). The brick also comes from different sources, with the *Quintanensia*, hardly present in the *Case a Giardino*, accounting for 66% of all the stamped bricks. These two buildings are also designed very differently, despite their similarity of basic function, making it clear that we are looking at the activity of two different architects or master builders, using different workmen and different suppliers of materials, and presumably working for different clients.

Many of the construction details found in the *Case a Giardino* also occur in other large construction projects of the early second century in Ostia. Most notable are the *Piccolo Mercato* (c. AD 114–118) and the whole zone of the Baths of Neptune including the residential *insulae* on the Via della Fontana (all c. AD 126–130). Although built entirely in brick, the latter have the same kind of string cornice detailing on the street façade as the *Case a Giardino* complex and share many similarities in plan as well as construction. Rough calculations suggest that the *Case a Giardino* may have needed at least 150 men working over 5 years to build, and the *Piccolo Mercato* at least 80. Although the evidence is very scanty, it is unlikely that any single building 'firm' at Ostia was this large. It is more likely that here we see evidence for a group of builders working under a major contractor (*redemptor*) who was wealthy and influential enough to be given public building contracts like the Baths of Neptune, funded by the emperor Hadrian, but also took on major residential and commercial construction projects, whether for the town itself, a private client looking for income from urban rental, or as a speculative development on his own account.

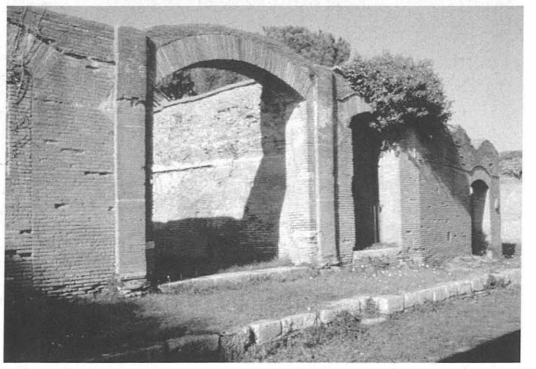


Figure 4
Ostia, *Case a Giardino*, SE façade



Figure 5
Ostia, *Caseggiato del Serapide*, internal court

This contractor would have organised the workforce, taking on both skilled builders for piecework and casual day-labourers as required (DeLaine, 2000b , 121–123; cf. Lancaster, 1998, 305–308). In projects of this size, neither the strong element of uniformity in overall technique, nor idiosyncratic but regular construction details such as the systematic use of travertine can be attributed to the individual workmen, but must depend on instructions from the contractor. Elements such as the alternation of face and interior brick noted in the *Case a Giardino*, on the other hand, could be due to either

contractor or workforce. That this detail is not merely 'normal' practice can be seen in the way the same transition is achieved in the piers of the *Portico degli Archi Trionfali* (V.xi.7), where the brick of the outer faces is keyed into that of the inner face in steps of 3–4 bricks rather than in alternate courses.

One of the implications is that individual workmen brought together for a one-off project could work to precise specifications given by the contractor, and this makes most sense if there was a basic body of common practice among the builders of Ostia. At the same time, the different ways of working apparent, for example, in different construction areas of the *Piccolo Mercato*, reveal different traditions either between contractors or within groups of builders. It could be argued that there were builders who specialised in the finework for pilastered façades, or in the piers and arches of porticoes such as those of the *Piccolo Mercato*. A contractor could therefore impose a set of detailed and uniform standards for the workforce, employ specialists for specific elements, or be content with more general instructions and leave the details for the actual builders to decide. In the latter case we would expect a large variety in minor details for large building projects.

At the same time there is evidence for individual small firms of builders, one of which can be identified in relation to a group of buildings which share construction details rather than materials (DeLaine 2002): III.i.6 on the Via degli Aurighi (c. AD 100, Figure 6); the *Caseggiato del Larario* (I.ix.3, c. AD 116); and the *Horrea Epagathiana* (I.viii.3, c. AD 137, Figure 7). Most significant are the distinctive L-shaped doors jambs, the use of decorative niches inside the buildings, and the extensive use of travertine as insets in doors and for the bases and sometimes capitals of the pedimented entrances. The buildings are also all very similar in concept, being small commercial markets with interior courts. The different patrons either provided the building materials, or constrained the builder in the choice of materials by setting a budget. In the case of the *Horrea Epagathiana* —the largest of these buildings and the most lavish in their use of materials— it appears that the clients were a pair of freedmen some of whose wealth was bound up in the trade of high-value goods (Pavolini, 1991, 103–104). The similarities are most likely due to a single master builder, who either selected the whole workforce



Figure 6
Ostia, *horrea* on the Via degli Aurighi, main entrance

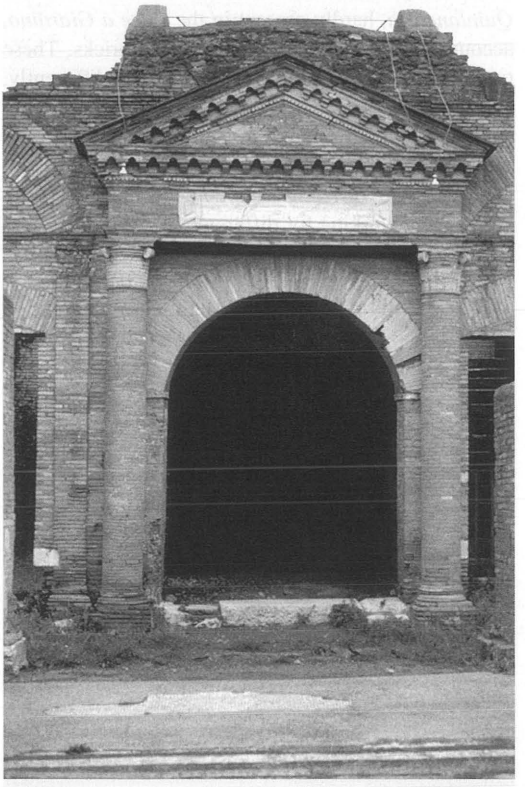


Figure 7
Ostia, *Horrea Epagathiana et Epaphroditiana*, main entrance

depending on the materials, or had a permanent workforce which could either deal with all aspects of the project whatever materials were provided or were responsible mainly for the special details. As all were fairly small projects, which could have built quite quickly over 2 to 5 years with a team of 16–20 men, we may here have either a single master builder or a strong family business operating over several decades at Ostia, erecting small but refined commercial and residential structures for private patrons with moderate resources.

The *fabri tignuarii* of Ostia

The relatively small size of the projects discussed above suggests that the architect/builder responsible for the *Horrea Epigathiana* was a local figure, who is likely to have been a member of Ostia's thriving *fabri tignuarii*. This *collegium*, one of the largest known at Ostia, had some 350 members by the end of the second century AD (Waltzing 1900, 4: 21–22; Wilson 1935, 52–65). This figure is derived from the most valuable surviving document relating to the *collegium* at Ostia, a statue base dedicated to the emperor Septimius Severus which bears a list of the names of 325 of the possible 350 members in AD 198 (*CIL* 14.4569). The *collegium* of the *fabri tignuarii* at Ostia appears to have been founded about AD 60 (Wilson 1932, 52) and was still active at the end of the third century AD (*CIL* 14.128; Waltzing 1899, 3: 609–610). Its wealth is evident from the main headquarters (I.xii.1) built near the Forum early in the second century and from the new temple (V.xi.1) they built near the theatre some 80 years later (Zevi 1971). Although it has been argued that their function was to ensure a place of burial, such *collegia* also provided feasts and other communal activities for the living. Since they needed an entrance fee to join, the members of the guild must have been of at least moderately good socio-economic status: successful small contractors or the heads of modest building 'firms' rather than individual building workers.

Exceptionally for Roman *collegia*, the *fabri tignuarii* had a quasi-military organisation. Its ordinary members were called the 'body of booted soldiers' (*numerus militum caligatorum*) and divided into 16 cohorts (*decuriae*) of 22 men, each headed by a chief officer (*decurio*). This is one possible source of the uniformity of building practice, as it presumably encouraged close ties which carried over into working relationships, especially where several members needed to band together in order to take on larger contracts than any individual could manage. That the *decuria* was the basis of such ties is suggested by an inscription (*CIL* 6.9405), which records the donation of 32 cremation places for the 22 named members of the tenth *decuria* of the *fabri tignuarii* at Rome, while the remaining 10 places are explicitly set aside for future members of the *decuria* (cf. Patterson 1992). At the head of the *collegium* were three *magistri quinquennales*, officials elected for a five year period. These were the executive officers who were responsible among other things for overseeing membership of the *collegium*, and for making dedications to important officials in the town or to the imperial family. In AD 198, the *quinquennales* were T. Claudius Sosipolis, Cn. Sergius Mercurius, and M. Licinius Privatus (*CIL* 14.128), who all appear as *decuriones* at the head of the 6th, 15th and 16th *decuriae* respectively. There are also inscriptions referring to a secretary (*scriba*, *CIL* 14.347, 418) who would have helped keep the records. The *collegium* also appears to have had a patron, called a *praefectus* (which might equally be a civil or military title), who in all the three cases we know of also held high office in the Ostian town council.

It is possible from the names on the list of AD 198 to say something about the background of the members, despite problems created by abbreviation and orthography (cf. Meiggs, 1973, 214–229). All the members appear to be freedmen or free born, not slaves, with at least two-thirds having last names (*cognomina*) which suggest that they were freedmen or of recent freed descent. Of these, many carry the clan names (*nomina*) of past emperors or important senatorial families of long standing at Rome, whose descendants or freedmen are well-known and common at Ostia. On the other hand, a number are clearly freedmen of old Ostian families such as the Egrilii or the Otacilii, or freedmen of their freedmen. There are some however whose *cognomina* suggest that they have come from further afield and/or arrived recently: for example, the *cognomen* of Faenius Latinus suggests that he comes from the area of Latium, on the fringes of Rome, where inscriptions of several other Faenii were found. Equally, Brittius

Oriens (?from 'the East'), Claudius Ptolemaeus (?from Ptolemaeus in Egypt), and Iulius Corinthianus (?from Corinth) have *cognomina* suggestive of origins elsewhere in the empire, although such names could equally be the whim of a slave's former owner.

Other names suggest adoption. It was common in the Roman world for a man to take his adoptive father's name, but to keep his own family name in adjectival form as a last name (e.g. Vettius Mucianus could be the son of a Mucius adopted by a Vettius). Although there are only about 20 of these in the list of AD 198, they may throw some light on the way that the trade was passed on. We know from the legal codes of a builder (*faber*) who bought and trained a slave acting on the express instructions of a friend (*Digest* 17.1.26.8). A successful trainee might then be taken into the 'family business', and ultimately be adopted as the builder's heir. It was also not uncommon for either a promising slave or a junior member of a family to be handed over for training in the same way. In the list under discussion, there are several cases where the adopted name and the original name suggest the adoptee was from the same extended family as the adopter (e.g. Valerius Valerianus). Given the rareness of the family name, Fulcinius Fulcinianus and Fulcinius Ostiensis, both members of the same *decuria*, are likely to be from the same firm, one a junior member of the family adopted by a builder called Fulcinius, the other possibly a former public slave (hence the name 'Ostiensis') trained and freed by the same man or by a close relative.

For a very small number of the members of the *collegium* in AD 198 it is possible to fill out further details of their lives from other inscriptions. The more unusual the name, the more likely the attribution, and any reference to the *fabri tignuarii* makes the identification fairly certain. Thus Egrilius Ision of the 14th *decuria* is most likely the man of the same name recorded (*CIL* 14.347) as building a tomb to Aulus Egrilius Secundus Threptianus, a freeborn man who had risen to the position of town councillor at the nearby small settlement of Vicus Augustanus Laurentinus, and who had at one time been secretary to the *fabri tignuarii* and to the Ostian town council. Egrilius Ision appears to be a freedman rather than a son, and here again it is easy to see how his former owner might have used his position in the *collegium* to obtain training for a promising slave in a lucrative trade. In other cases we can infer that the former owners of freedmen *fabri tignuarii* may have had some considerable economic and/or social standing from the number of other freedmen of the same *nomen* appearing in contemporary membership lists for other *collegia*. Such links are especially common with the *fabri navales* (ship builders, *CIL* 14.256), some of the ferrymen (*CIL* 14.251, 252, 254), and the priests of the imperial cult (*augustales*). It can be argued that is was the political pressure, financial support, and/or access to wealthy clients due to the status and position of their former owners in Ostian society which allowed some individual freedmen builders the wherewithal to become members of the *collegium*.

Other individuals on the list of AD 198 appear themselves to have been of some standing outside the guild. Arrenus Appianus, second in the list of the first *decuria*, has been identified as the same man who was a local magistrate (*magister vici*) at Rome (*CIL* 6.766), while Cerellius Ieronimus of the third *decuria* also appears at Ostia as a priest (*pater* and *sacerdos*) in the *collegium* of the *dendrophores*, who served the cult of Magna Mater and Attis. Domitius Aterianus, second in the list of the twelfth *decuria*, was also a *pater* in the cult of Magna Mater, and gave a statue of Attis to another *collegium* associated with the cult, the *cannophori* (*CIL* 14.37). Gargilius Felix, member of the seventh *decuria*, provides another link with the *cannophori*, as he appears in a contemporary list of members whose birthdays are to celebrated by the *collegium* (*CIL* 14.326). More tenuously, Metilius Ias, officer of the fifth *decuria*, and Matilius (almost certainly for Metilius) Hylas of the eighth may well be freedmen of Metilia Acte, public priestess of Magna Mater whose husband Iunius Euhodus was a chief magistrate of the *fabri tignuarii* in the 160s AD. The name is otherwise rare at Ostia, and it would not be surprising to find freedmen of Metilia Acte as the priesthood was an exceptionally important position for a woman. The other major priesthood in which we find members of the *fabri tignuarii* is the *augustales*. Four members of the AD 198 *collegium* have Augustalis as a *cognomen*, which should indicate that they, or their fathers, held that priesthood. From other inscriptions covering the period from the late 60s to the 240s AD, we can identify a further seven *fabri tignuarii* who were also *augustales*, all but one of whom were also *quinquennales* of the *fabri tignuarii* (*CIL* 14.296, 297,

299, 330, 407, 418/419, 4656). All of these positions —*magister vici*, priests in the religious *collegia* attached to the Magna Mater, and *augustales*— were either limited to, or particularly attractive to, freed slaves whose legal status prevented them from holding magistracies in their local town council.

The holding of high office within these *collegia* required quite substantial levels of wealth (Duncan-Jones 1982, 146–155), and it was by the expenditure of that wealth men not of free birth could gain status and exercise power in the community. One Ostian inscription records gifts by an *augustalis* of 50,000 sesterces, for which he was honoured by a public statue (*CIL* 14.367). Although we do not know precisely why, Julius Tyrannus, *quinquennalis* in the 170s AD, was similarly honoured by a statue set up in the theatre precinct by decree of the town council 'for his merits' (*CIL* 14.370). The wealth of such men in the *fabri tignuarii* can be demonstrated independently. Domitius Aterianus was not only wealthy enough to donate a statue to the *cannephori*, but also to build a tomb for his wife Sallustia Crispina (*CIL* 14.912) (cf. Duncan-Jones 1982, 162–171). Several *quinquennales* of the *fabri tignuarii* purchased expensive marble sarcophagi for themselves and their wives, some decorated with bespoke mythological scenes, like that of Metilia Acte and her husband Iunius Euhodus portrayed as Alcestis and Admetus (Figure 8).

Some few office holders in the *fabri tignuarii* clearly were able to rise further in rank, or at least their children could do so. The step might be slight, like the son of Livius Anteros, *quinquennalis*, who was wealthy and influential enough to act as patron to either the *fabri tignuarii* or to the *fabri navales* (*CIL* 14.4656). The son of Fabius Eutychus, *quinquennalis* of the *fabri tignuarii* and himself possibly a freedman's son, gained election to the town council and rose even higher to the rank of Roman knight, which required a fortune of at least 400,000 sesterces (*CIL* 14.367, 4642). When the young man died, he was honoured with a public funeral and a magnificent tomb on the road leading in from Rome set up by his father Fabius, and an equestrian statue set up by the town council in the forum, the most prestigious position possible. In response, Fabius gave the town council a further 50,000 sesterces, to be distributed in his son's memory. A similarly spectacular career for an active member of the *fabri tignuarii* was that of M. Licinius Privatus, officer of the sixteenth *decuria* and *quinquennalis* in AD 198. Presumably a freedman, he was made an honorary member of the town council in return for his gift to them of 50,000 sesterces (*CIL* 14.374, Figure 9). His political and economic standing was sufficient for his sons and grandsons to become both town councillors at Ostia and Roman knights.



Figure 8
Sarcophagus of Iunius Euhodus, *quinquennalis* of the *fabri tignarii*, and his wife Metilia Acte, public priestess of Magna Mater, Vatican Museum.

One of the questions which arises from such careers is how these men at the upper levels of Ostian society made their money. The only member of the guild who clearly appears to have started life as someone of high social and economic standing is Carminius Parthenopeus, a member of the town council and Roman knight in his own right, as well as *quinquennalis* of the *fabri tignuarii* (*CIL* 14.314). In the case of M. Licinius Privatus, his statue was set up by the whole *collegium* for his 'affection and good offices' towards them. The distinction of being granted both a special seat at the theatre and a place for his statue in the theatre precinct by decree of the town council, suggests that Privatus might have been involved in organising contracts for the substantial rebuilding and enlargement of the theatre, dedicated in AD 196 about the time that he was *quinquennalis*. That contractors (*redemptores*) who organised public building could also be magistrates in the *fabri tignuarii* is shown by T. Claudius Onesimus from Rome, who was a contractor on imperial building projects and a *quinquennalis* (*CIL* 6.9034).

Privatus seems however not just to have been involved in building. As well as his position in the *fabri tignuarii* he was later treasurer and *quinquennalis* in the *collegium* of the millers and bakers at Ostia and Portus. Although we know less about him, Valerius Threptus, *quinquennalis* of the *fabri tignuarii* at an



Figure 9
Ostia, *Piazzale delle Corporazione*, inscribed statue base to M. Licinius Privatus

unknown date, was also involved in different commercial *collegia*. One of these honoured the presiding deity of the Forum Vinarium, where he was again *quinquennalis*, while he was also an official of the guild of wine importers and merchants which met in the same forum (*CIL* 14.430, Coarelli 1996). In this case it appears that Threptus began working at the wine forum, and only later acquired interests, and influence, among the builders. The name of Hadriaticus Felix, a member of the twelfth *decuria* of the *fabri tignuarii* of AD 198, suggests that this link between builders and wine merchants was not exceptional, as other inscriptions show that the activities of the wine merchants were particularly associated with the Adriatic (Meiggs, 1973, 275–276).

Close links between high-ranking members of the *fabri tignarii* and other guilds connected with Ostia's broader economic role as the harbour city for Rome is seen also in their *praefecti*. Most revealing is P. Aufidius Fortis, who by AD 146 was the patron of the whole town (*CIL* 14.4621). Earlier he had been *praefectus* of the *fabri tignuarii*, patron of the grain measurers and salvage divers, and permanent president of the grain merchants. This latter position and his membership of the town council at Hippo Regius in North Africa suggests that he may have come to Ostia himself as a grain merchant and decided to stay (Meiggs 1973, 203), possibly importing grain for the Roman state. He appears also to have been a man of sound financial sense, as he was ultimately treasurer of the colony on five occasions. Although the precise detail is missing, his activity roughly coincides with the period of great building projects at Ostia, some of which had imperial funding and even more may have been built by the town itself (DeLaine 2002).

The large-scale projects such as the *Piccolo Mercato* and the Baths of Neptune and associated *insulae* discussed above would have needed sound financial management and an efficient and organised building industry to be successful. Also important for this period of intensive building in the 120s and 130s AD would have been the continued viability of individual 'firms', the maintenance of a sustainable cash flow allowing the builders to be paid and thus discouraging them from moving their business elsewhere, particularly to Rome, and some control over priorities to allow public building projects to take precedence over private. That this in fact happened is suggested by evidence from the *Case a Giardino*, where excavation has shown that there was a gap of several years between laying the foundations of the development and beginning the superstructure (Zevi and Pohl, 1970, 73–74). The intervening period saw a major, probably civic, project involving the reorganisation of the northern end of the Forum and the building of a grand approach to it from the Tiber, the *Portico di Pio IX* , and the building or rebuilding of several commercial buildings including the *Piccolo Mercato*, whose builders may have worked later on the *Case a Giardino*. Whatever the reason for construction to be concentrated in this area of Ostia in the second decade of the second century —and some form of natural disaster such as flood or fire is the

most likely explanation— the concurrent temporary abandonment of the *Case a Giardino* suggests some active control or constraint over the activities of building 'firms'. By the end of the second century, the legal sources make it clear that the *collegium* of the *fabri tignuarii* was believed to exist for the benefit of public building works (*Digest* 50.6.6.5.12). Although proof is lacking, it is possible to imagine how the involvement of someone like Aufidius Fortis, who had a substantial control over public finances at Ostia, could use his position to negotiate with the members of the *collegium* by offering them lucrative public contracts with assured financial backing.

Conclusions

The builders known to be active in the *collegium* of the *fabri tignarii* of Ostia have been shown to be fully integrated into Ostian society in so far as their legal status allowed. The obvious wealth of some members, especially the *quinquennales*, their presence in other religious and commerical *collegia*, and their connections with the Ostia town council and members of important new or established Ostian families, all suggest that individual builders had considerable status within the community, which in a few cases led to their descendants rising to high position locally and within wider Roman society. At the same time, the quasi-military organisation of the *collegium* created a mechanism whereby large civic building projects could be prioritised, organised, and implemented to a high and uniform standard, through the mediation of these same individuals. The same network of connections appears also to have been instrumental in bringing new blood into the industry through the training of slaves or junior members of these families in the building trade, and is one likely source of private contracts for building firms. If by the end of the second century it was believed that the *collegia* existed for the benefit of the state and its building projects, there is little doubt that at Ostia the benefits were mutual.

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Notes

1. All original photographs are by the author.
2. Ostian buildings are identified by region, block and unit number as indicated on the 1:500 plans in Calza 1953.

Abbreviations:

CIL - Corpus Inscriptionum Latinarum

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Roman roads in Croatia

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Romans were the most efficient and systematic road constructors in ancient times. They built about 100.000 km of roads from which only 14.000 km on the territory of modern state of Italy.

Romans road constructors particularly improved the pavement construction. They paid special attention to the road foundation (base course) and probably because of that we still have so many remains of their roads all over ancient Roman Empire.

Pavement construction of roman roads, speaking in the modern technical terms, was a type of rigid pavement construction. They also used in pavement construction their great invention, the cement mixture from the site near ancient town of Puzzoli in Italy. Pavement construction had maximum of four different layers called statumen, rudus, nucleus and summum dorsum. Depending on the road placement and importance in the road network, roads had very different geometrical characteristics (pavement construction, width etc.)

The territory of the present state of Croatia was a part of the Roman Empire, thus the Roman legions and domestic people built the roads in this region as well. The Roman road network on the Croatian territory was very dense and was connecting the main settlements of that period in the coastal part and in the continental part of today's Croatia, like: Parenzium-Poreè, Pola-Pula, Iadera-Zadar, Salona_Solin, Narona-Vid, Epidaurum-Cavtat, Siscia-Sisak, Cibalia-Vinkovci etc.

The main aim of this work is to, along with the concise presentation of the main constructing principles of the Roman roads, give review of presumable and confirmed Roman roads in Croatia and their importance in the entire road network of the Roman Empire.

> The Romans were the first people to understand that the road counts less than the places it connects. The road between two towns bears the meaning only for these two places. What is important for the whole territory of the empire is the dense network of roads, the endless ribbon running everywhere. In the Roman empire the traffic played such an important role as the blood circulation plays in a human body. All the ways should have been passable and should not have closed down due to repairs. Nobody knows who invented the road. The Roman censors, consuls, emperors, generals and soldiers were the people who developed the road network. Hermann Schreiber, *The Symphony of the Road* [1].

Roman Roads

The organized construction of roads has been known for 5000 years. The first roads with arranged stone paving for the needs of religious processions dates back into 2000 B.C. in Babylonia. The Assyrians and Etruscans were known as skillful road constructors. The Minoans and Carthaginians paid attention to pavement

construction, and the Phoenicians and Egyptians showed remarkable precision in measurements and surveying.

The most successful and well-organized road constructors of systematic paving of the Antiquity were undoubtedly the Romans. They realized early that well road connections in the Empire would facilitate military operations and enhance the quality of everyday life, so they connected all conquered areas. An organized road construction started around 334 B.C. According to one source the Romans built about 90.000 km, and according to the other about 150.000 km of roads by the time of the height of the power. 14.000 km of roads were built on the territory of today's Italy [2].

The Romans took over the knowledge of road-making from the Etruscans. The Romans improved the pavement construction with emphasis on the foundation construction and drainage system. If one takes a look at the roads built in different periods of the Roman Empire it can be concluded that they had been gradually developing their building methods over the centuries. Due to different building materials, available «tools», landscape and climatic characteristics the road construction varied in different areas. The «tools» e.g. in distant provinces were more primitive.

The Senate created the road legal system. It approved the financing of the roads and passed the laws. As early as 123 B.C. the folk tribune Caius Cracchus passed a law on roads —lex viaria [3]. The roads were built not only by the Emperor but, more or less voluntarily, also by the powerful Romans after whom they were named— Via Flaminia, Via Appia. The roads were built by soldiers in the rests between wars and, to a large extent by the locals of the relevant area. All the builders in the ancient Rome were named architects and they designed the roads. In the beginning, the engineers were of the Greek origin transmitting their knowledge to the young Romans. The roads were maintained by edili who took care of traffic and public safety.

The mile —stones were laid along the road. They were 3 m high stone piles with marked distances to the closest town, and to the province border or there was the name of the ruling censor, consul or Emperor. The distances were measured in Roman miles; 1 mile stands for 1,480 meters.

Classification-geometrical characteristics

The main characteristic of Etruscan and early Roman roads in the terms of road stretching was the «straight line». Such a road stretching prevented constructors from building the roads in a hilly, undulating terrain in the Alps and mountains. The longitudinal slope on the roads was on average 5–7% and on the route sections of the extremely inconvenient terrain the segments were embedded with grading 14–15%, even to 20%, which was acceptable for pedestrians and two-wheel chariots.

The type and the width of the road were interconnected within the road network as all the Roman roads were classified.

- *Via* with widths of 2,37 m and 4,14 m was a road for heavy traffic. As a rule it was 2,96 and 3,56 m wide and thus adjusted to the distance of 86 cm wheels for two-lane and three-lane roads. There were extensions on the serpentines for the width of 4,74 m. The small radii of horizontal curves and a number of hauling animals determined the width.
- *Actus* was a 1,19 m wide one-lane path for hauling animals. The same term was applied to footpaths in the towns. All mountain roads with little traffic were 1,19 m wide.
- *Iter* (the half of actus) was a 60 cm path for pedestrians and riders.
- *Semita* was a half an iter wide (30 cm) boundary path, on the border of meadows, pastures and ways in the hills.

If provided with pedestrian ways urban roads were 7,0 m wide. Without them they were 4,15 m wide. The sidewalks were 1,5 m wide, which is still present-day standard considering two pedestrians passing each other.

The above classifications did not include roads of special importance such as those in Rome, or those intended for religious or imperial processions. Those roads like via Appia were even up to 12 meters wide.

Pavement construction

The pavement construction should have been durable. The engineering progress enabled systematic

approach to construction and the adjustment to traffic requirements, soil contents and climatic conditions.

The road construction started with legionaries —war prisoners or slaves digging a furrow in the direction and width of the proposed road. Then the excavations started in the form of the canal waterbed with canal borders topped with stones.

According to modern terminology the Roman road constructors built a rigid pavement construction that comprised 3 to 4 layers laid on the prepared foundation. The number of the strata depended on the road significance.

The «statumen» is the bottom layer made of stone aggregate. The aggregates were of the size of at least 5 cm and the total thickness of 25 cm to 60 cm;

The «rudus» is laid upon the basic layer «statumen» that was cemented with granulated material (aggregates under 5 cm) with the total thickness of 25 cm;

The «nucleus» is a layer embedded only on the important roads, made up of cemented tiny granulation with total thickness of 30 cm;

The «Summum dorsum» or «summa crusta» is a surfacing made up of large rectangular or polygonal two inch stone slabs stabilized with cement.

The layers were horizontal in the transversal cross section, aside from the paving «summum dorsum» or «summa crusta» that had a lateral grade 1:60 in the transversal direction.

The Romans had used the lime mortar —known already by the Greeks since the third century B.C.— and experimented with it in the road construction. By mixing lime with different gravel types they got so called caementum. Next to the discovery of puzollana, a natural volcanic tufa called after the site Puteoli near Naples, those materials enabled the construction of a rigid pavement of a high quality.

In this way the pavement construction was circa 1,00 m thick, and as all the layers were stabilized in the above-depicted manner the pavement was built as a «lying wall». The load of heavy wagons with a harness often caused cracks in the rigid pavement construction.

The pavement of inaccessible and rarely used ways in the Alps and in rugged terrain was shaped mostly as a piece of a ground carved out in the rocks with widths usually narrower than the standard ones.

A typical cross section of the Roman road is seen in Figure 1.

Roman Roads in Croatia

Roman empire in Croatia

As far as it is known the oldest people of present-day Croatia were Illyrians. Approximately in the third century B.C. the Romans under the Emperor Octavius and Augustus started fighting against Illyrians. The Emperor's stepson Tiberius finally conquered Illyrian and Celtic tribes in A.D. 8 (or A.D.9) in the battle north from today' s Vinkovci (called then Cibalae).

United by then, the province of Illyria was divided into the provinces Dalmatia —Dalmatia (from the Adriatic sea to the river Drina and Savus (Sava)) and the province Pannonia (a part of Croatia, of northern Bosnia and a part of Slovenia) in A. D.10. A today's peninsula Histria (Istria-a part of Croatia) was joined to the province Venetia.

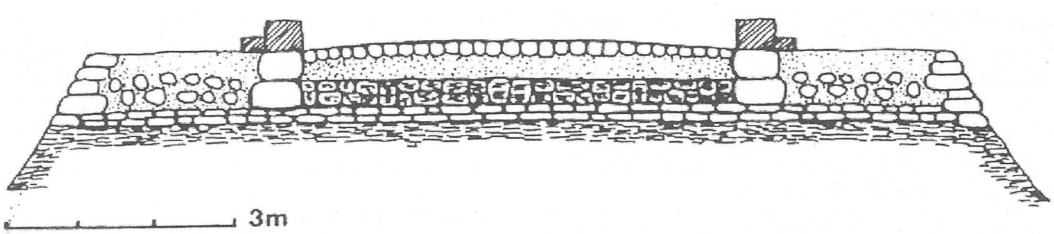


Figure 1
The cross section of the main Roman road [4]



Figure 2
Roman provinces in today's Croatia [5]

In the third century the Emperor Diocletian, following his reforms, divided the Empire into smaller administrative units, so there were six to seven provinces in Croatia. The capitals were the cities Salona (Solin) and Siscia (Sisak).

After the final division of the Roman Empire into the Western and Eastern Empire in the year 395 the whole territory of Croatia belonged to the Western Roman Empire.

In all possessed areas, so in Pannonia and Dalmatia, the Romans built first fortified camps and military roads. They developed trade and crafts in the towns, and in the neighbouring areas like Bosnia they stipulated farming and mining. Over the five centuries of their rule the Romans created a dense network of roads and connected it across Aquilea —the center of the province of Venetia— with the road Via Flaminia that led to Rome.

Many Croatian cities are built on the foundations of Roman settlements: Siscia (Sisak), Mursa (Osijek), Epidaurum (Cavtat), Cibalae (Vinkovci), Tarsatica (Trsat/Rijeka). Several cities are still archeological sites such as the city of Salona (near Solin), and Andautonia (Ščitarjevo near Zagreb). The most recent and quite a rich site that has been intensively excavated in 1994–1995 is Narona near Metković [5]. The same history is shared by the roads built in Roman times that connected the mentioned towns with the remaining part of the Empire. Several Roman roads were used in the succedding centuries for the construction of modern roads. Some of them can still be studied on some sections in their original form.

One of the finest and most comprehensive sources on the network of the Roman roads is Tabula Peutingeriana. Tabula Peutingeriana is a copy of Castorius' map. It was found in a Benedictine monastery in Bavaria. Tabula Peutingeriana contained originally 12 pieces of parchment of the total length of 6,8 m. Eleven parchments have been preserved. Today they are to be found in the Austrian National Library in Vienna [6]. The Castorius map is supposed to have been created around 273 during the land surveying. The map serves as a basic source of the geography of earth, as comprehensive and precise as it could have been with the measuring methods of that time. The Castorius map comprises the roads, distances between province stations, camp types, coastal characteristics of the Adriatic Sea, flows and river basins of Croatian largest rivers and mountains.

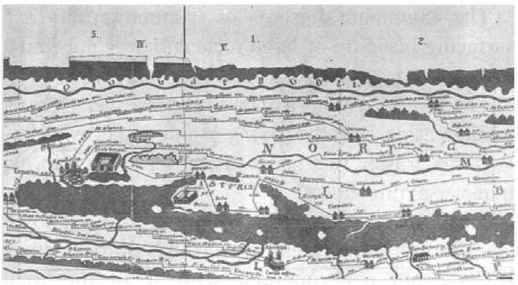


Figure 3
Tabula Peutingeriana [7]

Coastal area-provinces *Dalmatia* and *Histria*

Many towns in the coastal part of Croatia, both on the mainland and on all large islands developed from the Roman settlements. Next to seaways, the Romans also used the roads as the safest ways for military movements on both sides of the Adriatic.

Roman settlements of special importance that possessed all Roman civil rights had the status of colonies. There were more colonies on the coastal side than in the mainland. Connected by roads with the center of the Empire the colonies were the porters of the Roman power and progress.

There was one major road along the coast with the evidenced route mentioned in all the sources as an important traffic direction [4], [8].

The road connected:

— Aquilea-Tergeste (Trieste/Italy) and Tarsatica (Trsat-Rijeka) over the continental part of Istria. The road was called *Via Gemina.*
From Tarstatica the route led to settlements-travel stations:
• Senia (Senj) over the Velebit mountain to Arupium (Otočec) - Epidotio (Kvarte) - Ancus (Kula) - Ausancalione (Lovinac) - Clambetis (Obrovac) - Hadre ab Madre (Medvida) - Burnomilia (Ivoševci near Široka stijena close to Kistanje) and diverged farther into two directions, first Iadera (Zadar) - Scarda (Skradin) - Tragurium (Trogir) - Salona (Solin-Split) and second direction Promona (Drniš) - Andretio (Muæ Gornji) - Salona (Solin).

There are inditions that ther was another one direction which lead from the Senia (Senj) to the south but direction was not confirmed [2].

Tabula Peutingeriana mentions the route from Tarsatica (Trsat-Rijeka) to Salona (Solin) via Promona (Drniš). The distance between Tarsatica (Trsat-Rijeka) and Salona (Solin) was 182 mile (circa 273 km). Outside Salona (Solin) the road ran further across Dalmatia (Dalmacija) connecting Narona (Nin) and Epidaur (Cavtat).

Roman sites are very well explored and preserved on the Istrian peninsula. Noteworthy is *Via Flavia,* a consular road connecting Tergeste (Trieste) and Pola (Pula). The construction of the road started in 130 B.C. The route began in Aquilea and went on via Tergeste (Trieste-Italy), via Quoev (Istarske toplice) and via Parenzium (Poreč) to Pola (Pula).

According to Tabula Peutingeriana the total length of the road between Tergestica (Trieste) and Parenzium (Poreč) [9] was 48 Roman miles (circa 72 km), and from Parenzium (Poreč) to Pola (Pula) 30 miles (circa 45 km).

This road passed near Parenzium (Poreč), an important settlement developed from the fortified camp (castrum) into the colony (colonia Iulia). The remains of the road considered as via publica are to be found in the settlements Pizuga and near Limski kanal [10]. It is interesting that the part of the modern highway passing the western part of the Istrian peninsula is constructed on the old Roman route. Figure 5 shows a stretch of Vižinada to Parenzium (Poreč) road with a typical Roman straight way of



Figure 4
An ancient Roman Road cut into the mountain Snježnik near Tarsatica (Trsat-Rijeka)

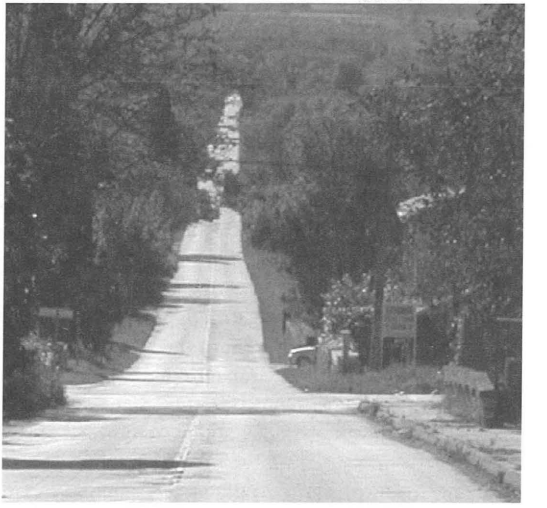


Figure 5
Stretch of Vižinada to *Parenzium* (Poreč) road with a typical Roman straight way of laying the route

laying the route. As the road connects the tourist resorts it has great significance for this area.

Via Flavia ran from Pola (Pula) colony along the eastern coast of today' s Istria connecting:

Nesactium (Nezakcij) - Mausio Arsia (Rakalj) - Alvona (Labin), Lovriana (Lovran) - Tarsatica (Trsat - Rijeka). The road might have crossed the one reaching Tarsatica (Trsat - Rijeka) from the direction of Tergestica (Trieste) on today' s area of Kastav, but so far this road has not been dug out.

The total length of Pola (Pula) - Tarsatica (Trsat - Rijeka) road was 48 Roman miles (circa 82 km).

In Dalmatia a dense network of Roman roads was laid in the regions of Iadera (Zadar), Salona (Solin), Narona (Vid) and Epidaurum (Cavtat).

From Iadera (Zadar) the road diverged into three directions [11]. A road, which can be seen today from the air, led to Aenona (Nin) that was otherwise separated from the main coastal road and primarily directed to sea traffic. The other road led to Nedinum (Benkovac) westward and was linked to the mainland way towards Salona (Solin). The main route from Iadera (Zadar) led southward, along the coast via Scardona (Skradin) and Tragurium (Trogir) to the colonies Salona (Solin) and farther Narona (Vid).

Not less than five roads connected the colony of Salona (Solin) with the harbour and the sea. As most Roman settlements Salona (Solin) was located on the hill above the sea and the later built Diocletian' s summer residence in Spaletum (Split). Salona (Solin) was among the largest and most developed settlements in the Croatian part of the Adriatic. At the hight of its prosperity Salona (Solin) had around 20.000 inhabitants, but some historians claim to have them even 60.000 (the fact based on the number of seats in the amphetheater). The town had an infrastructure of roads which has not been fully explored so far as the financial means are lacking. As evidented in many documents the urban roads were built here by the army. Most roads were built in the early first century A. D. A part of the main town road can be seen on the archaelogical site under magnificent town gates called Porta Caesarea (Figure 6). The road heading under above mentioned Porta Caesarea from Salona eastward next to the ancient city runs over the arm of the River Salon (today Jadro). In this section the road is laid on the masonry stone arches —a specific masonry bridge the part of which still exists as a testimony of Roman skilfulness



Figure 6
Porta Caesarea [12]

(Figure 7). This find is called by the locals «Five Bridges».

The road that ran from Salona (Solin) northeast to the continental part and to the mainland of the Biokovo mountain by the Roman settlement of Tilurio (Trilj), Ad Nova (Runović-Imotski) to Narona (Vid) was 65 miles long (circa 98 km). Narona (Vid) is another important colony where the excavations have started only recently. Along the river Naro (Neretva) Narona (Vid) was connected with Bosnia and mines of silver and gold which were of particular interest for the Romans.

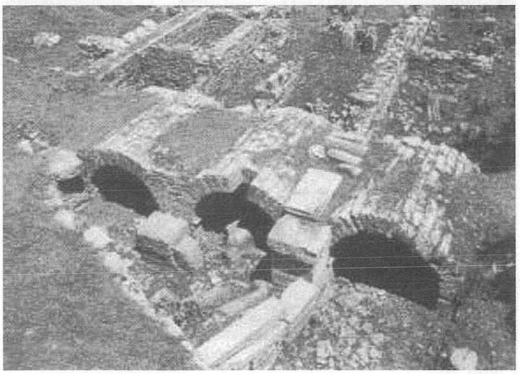


Figure 7
«Five Bridges»[12]

This road as a combination of a route in the mainland ran from Narona (Vid) to Ad Hihia (Trebinje in Montenegro) and farther to the sea, along the coast to the settlement Asamo (Slano) it continued to Epidaurum (Cavtat) the farthest colony in the southern part of Croatia. This segment of the road was 182 miles long (circa 273 km). The road connected Epidaurum (Cavtat) with the mountainous hinterland (which is today the territory of the state of Montenegro). At Ad Hihio (today Mosko) the road diverged into three directions: already mentioned road to the valley of Drina and Salona (Solin), towards Anderba (Nikšić) and to the west to Scodra (Skadar).

Despite the same principles of construction, the quality of roads varied depending on supplies and quality of masonry material of relevant areas. The craft of masonry was highly developed for the construction of harbours, settlements and roads in the coastal part of Croatia. The supplies of limestone in the open quarries (cava) facilitated the construction of durable and quality Roman roads in this area. Figures 8 (a and b) show the roads close to Iadera (Zadar) and in Salona (Solin) paved with limestone. The construction of surfacing depended also on the location of the road, so the pavement of urban roads (b) differs from that in the country (a).

Continental region-province Pannonia

As in other provinces the centralized Roman power «deeply dug» the stretches of ancient roads in these regions. They were used for centuries after the fall of Roman Empire. There is an evidence that as early as in the first century B.C. one of two major roads crossed the continental part of today' s Croatia. It was only at the beginning of a new era that Pannonia joined the network of Roman roads and became of interest for the Romas state. The major route that is mationed already in the first century B.C. Via Pannonia got its name after the province it crossed in the west-east direction. The stations that are mentioned as well are Aquilea-Nevoidunum (Drnovo in Slovenia near Novo Mesto), Servitium (Stara Gradiška), Marsonia (Slavonski Brod), Sirmium (Sremska Mitrovica in Serbia) and further across Serbia and Bulgaria to Byzantium (Bizant)[3].

As Balkan Peninsula dominated over the central area of the Roman Empire a dense network of good roads was constructed in the third century A. D. The starting point of all roads was Aquilea with three stretches: northern, central and southern one. A part of the northern route that ran along the Drava in our area connected military, rural and urban centers like Poetovia (Ptuj) and Mursa (Osijek). According to Tabula Peutingeriana the route was 156 miles long (234 km)[3]. Aqua Viva (Petrijanec) and farther to the east Iovia (Ludbreg), Sunsita (Kunovec breg), Piretis (Draganovac near Koprivnica), Letulis (probably Virje), and Serota (Virovitica) were located on this route [13]. The central route, *Via Pannonia* ran along aready known line, Emona (Ljubljana in Slovenia), Siscia (Sisak) and Sirmium (Sremska Mitrovica in Serbia) with several already

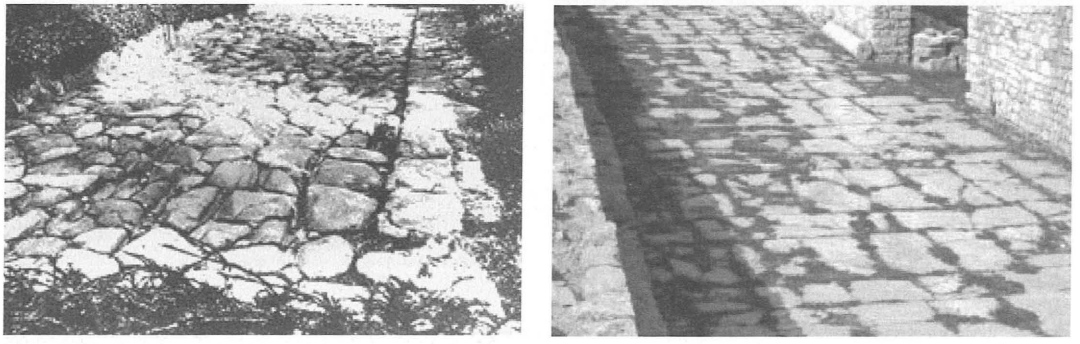


Figure 8
A typical pavement of masonry and limestone slabs on the Roman roads
a) in the coastal area of Croatia outside the town near Iadera (Zadar)
b) in the town Salona (Solin)

then mentioned stations. According to Tabula Peutingeriana a part of this road running across the territory of today' s Croatia was 110 miles long (167 km)[3]. A southern, already mentioned route ran along the coast of the Republic of Croatia. Five roads are mentioned in this period connecting the southern road with the central one, of which Senia (Senj) to Siscia (Sisak) was on the territiry of Croatia.

On the territory of Croatian Zagorje there were two major north-south roads. One followed the flow of Krapinica and Krapina and joined over Bednja and Dravsko polje the poetovian region in the north and across the southern part Siscia (Sisak) and Andautonija (Ščitarjevo). The other route reached the southern slopes of Ivanèica across the plain of the river Reka. This road joined the road Poetovio (Ptuj) and Mursa (Osijek) across the mountain in the north, and across Medvednica continued to the south in the direction of Andautonia (Ščitarjevo). This system of roads included secondary roads as well. There is much evidence of it, for instance the remains of the Roman road that ran across the town Sv. Ivan Zelina. The archaelogical finds confirmed the existence of the Roman settlement Pyrri (Sv. Ivan Zelina) near Komin, and a lively traffic along Poetovia (Ptuj) to Siscia (Sisak) road, [14]. It is also known that from Aqua Viva (Petrijanec) the road led over Andautonia (Ščitarjevo) and Pyrri (Sv. Ivan Zelina) to Siscia (Sisak).



Figure 9
Part of the main Roman urban road through Andauntonia with the stone edge, paved with stone slabs and porches by the both side
a) reconstruction according to the ancient writers;
b) road with preserved bases of the colums-colunades;
c) groove for theforced guiding vehicle

In the road network between the rivers Mura and Drava the north bound route direction from Poetovia (Ptuj) to the military camp in Carnunitum (Petronell) was of special importance. The road connected here the banks of Drava with the crossing over the Mura where the ancient settlement Halicanum (Martin on Mura) was built. On the territory of Me?????imurje, beside the mentioned road there is another one that led from Poetovian region eastbound, crossing Mura, and continuing to the northeast in the direction of Aquincum (Budapest).

On the territory of today 's eastern Croatia there was Cibalae (Vinkovci), a city that due to its very convenient location at the crossroads of important land routes gained the status of a colony with full municipal rights as early as the first century. From Cibalae (Vinkovci) the road diverged to the east from Sirmium (Sremska Mitrovica in Serbia) to the west over Siscia (Sisak) to Emona (Ljubljana in Slovenia) along the Drava to Poetovio (Ptuj), farther, over Marsonia (Slavonski Brod), across Bosnia to Salona (Split), and in the north across Mursa (Osijek) to Aquineum (Budim) and farther to the west [15]. From Cibalae (Vinkovci) another road led in the direction of Marsonia (Slavonski Brod) across Certis (Đakovo) and joined the already mentioned Siscia (Sisak) to Sirmium (Sremska Mitrovica) road running along the right coast of the Sava river.

Through Slavonia ran less important roads like Picentium (between Pleternica and Podgorača), Stranianae (between Našice and Orahovica), Aqua Balissa (close to Pakrac), Varianae (close to Kutina) and Siscia (Sisak) led from Certis (Đakovo) .

Aside from those most significant roads connecting Roman provinces, there was also a thick network of less important roads linking municipia and colonies of the Pannonia region.

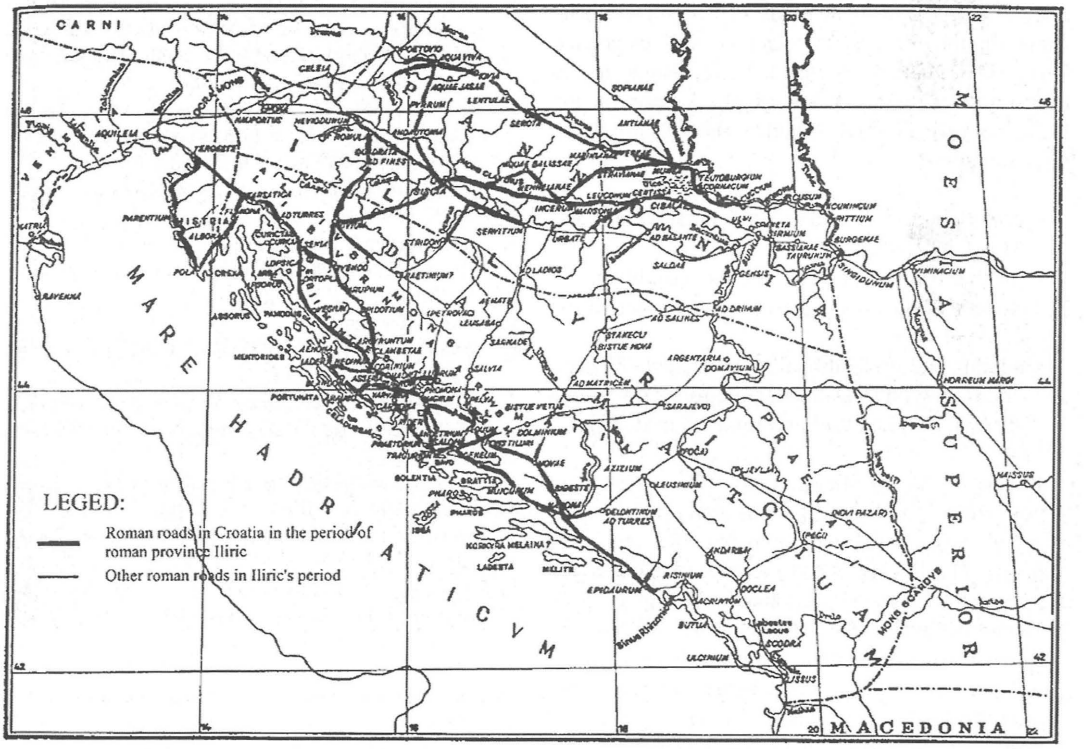


Figure 10
Roman roads during the Roman Empire in the province Iliric [16]

Conclusion

From our point of view the Roman achievements created without any help of present-day technology 2000 years ago are really stupendous. Many of them, especially Roman roads and the dense network throughout the whole of Europe still exist today.

What is exceptional about these roads is a precise design of a pavement construction. The technological advancements of the Romans can be seen even in the most modern types of rigid (concrete) pavements. Lower bearing layers made of unbound masonry material, and upper strata and the paving bound with cement (or other material) are a consistent part of the then and the present-day pavements. Due to carefully constructed foundation and well performed drainage the depicted Roman roads can still be explored and studied today.

There are many remains from the Roman age on the territory of Croatia. This paper strives to give a review of major Roman roads in Croatia with the stress on the remains that can be still excavated today. The major roads that led from Rome to the territory of Croatia started in the centre of the Province Venetia, from Aquilea and diverged into three directions:

- northbound to Poetovio (Ptuj in Slovenia) and Mursa (Osijek),
- in the central part to Emona (Ljubljana in Slovenia) and Siscia (Sisak), and further to the east and
- southbound in the direction Tergestica (Trieste), and farther on to Dalmatian metropolises Salona (Solin), Narona (Vid) and Epidaurum (Cavtat).

In this way all specific characteristics of the terrain were respected locating the roads along the rivers or along the coast, using the mountain passes (e.g. over Velebit). The linking of the provinces Dalmatia and Pannonia over the central mountainous region of the present-day Croatia was avoided in this way. There is only one road in this region, the Senia (Senj) to Siscia (Sisak) road running along the longer and the milder route through the river valley of today' s Lika, and avoiding the hilly area of Gorski Kotar where the rugged terrain still presents problems in the modern road-making.

Because of lacking finances, not all known sites have been explored. Salona (Solin), one of the principal cities of the Roman age and the seat of Dalmatia has been only partially excavated. Only a few remains can be studied, and there is no possibility of studying the structure of the pavement on the major roads of this settlement. The same case is the site of Narona (Vid) and Andautonia (Ščitarjevo).

There is also another problem in exploring the Roman roads, as many of them are located outside the organized museological space and thus stay unmarked and neglected. Every and even the smallest remain of the road, path or way should be marked even if they make up the basis of the modern roads or an archeological park.

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Learning from stone traditional vaulted systems for the contemporary project of architecture. The experimental construction site at the Ponton de la Oliva (Spain, 1851–1858): Survey of the small «boveda plana» of the Casa de Mina de Limpia, and reconstructive hypothesis for the Casa del Guarda flat-vault

Eliana de Nichilo

In the latest years there is a growing interest for the revaluation of the European tradition, culture and constructive natural materials (i.e. stone), and for the elaboration of a new rehabilitation strategy in the light of a sustainable management and preservation of cultural heritage.

In the European area, characterised by the generalised use of load-bearing masonry systems with an organic character in traditional construction, the typological and constructive reform of traditional vaulted systems is a central question. The importance and cohesion of this cultural area, but also the extremely diffuse use of stone techniques, enables us to propose their reintroduction into contemporary restoration and constructive practices.

For many years the architectural research has been dominated by the use of «new materials» and the interest on vaulted systems (especially made in stone), has been relegated only in the direction of historical studies and in that of surveys and reconstructive analysis.

The complex examples of vaulted systems contained in the historical treatises on stereotomy, have been basically «ignored» in the architectural and engineering practice in favour of an exemplified and reductive «modernist» formal repertory.

In the next years, architects will be mainly involved in a complex work of re-assessment and renovation of both historic landscapes and of the urban environments, and the recognition of the intrinsic qualities of traditional materials and techniques (in terms of durability, performance, aesthetic quality, etc.) is self-evidently urgent, such as the elaboration of updated architectural solutions for stone vaulted systems.

A first attempt in this regard is represented by the model of a reinforced «flat-vaulted» system, specifically elaborated for the reconstruction of the *Casa del Guarda* covering system, at the experimental construction site at the Pontòn de la Oliva (Spain, 1851–58), that could also be regarded as a remarkable example of a stereotomical application in hydraulics. In fifties it was substituted with a reinforced concrete roof.

The project of the earth dam at the Pontòn de la Oliva at the beginning of the Canal Isabel II (the channel which still provides water to the city of Madrid), reflects the social and productive situation of the country during the last century. In Spain the long tradition of stone techniques, achieved in the previous centuries and formalised in the Spanish historical treatises, was utilised for solving the problem of resisting the water pressure force by means of a cut-stone masonry structure.

This well-established and long tradition is an important element for the comprehension of the formal and constructive characters of the interesting solutions realised within the site, such as the unique and original example of the «flat-vaulted» system at the «Casa de Mina de Limpia».

The analysis of the survey data of this dry-assembled stone masonry flat-vault was the preliminary condition for the elaboration of the reconstructive hypothesis.

The great problem before the «modern era of concrete» was the use of no-tension materials (such as clay and mud or masonry) to face flexural out of plane actions, to which these materials are not able to react appropriately. For this reason specific tectonic knots, solutions of contact surfaces among elements and of chain and supporting elements had been elaborated and improved.

Therefore the paper intends to highlights the tectonic principles and the traditional syntax, and to explain the complex passage from the geometrical model to the real model of the «flat-vaulted» system, throughout the graphical one (which also involves a reflection on the updating of traditional stonecutting methods, i.e. cad-cam processes).

Stone Techniques for the Nineteenth-century Territory's Infrastructures: the project of the Canal Isabel II

On 16th July 1851 the Administrative Council[1] of Canal Isabel II appointed four engineers of the *Cuerpo de caminos, canales y puertos* for the redaction of the executive project of the canal derived by the Lozoya river, that, in the following years, had to almost duplicate the water supply of the city of Madrid (Fig. 1).

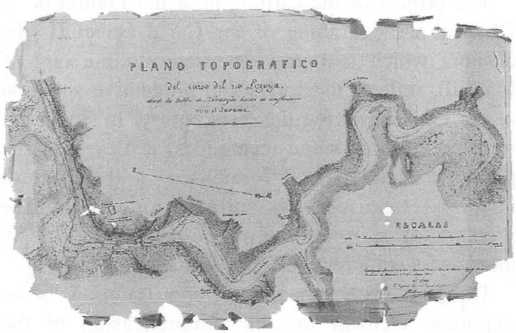


Figure 1
Planos generales del Canal Idabel II (1851). Archivo Central del Ministerio de Fomento. (supplied by J. J. Gonzales Reglero)

The project of Canal Isabel II was a political and technological event. On the one hand the President of the Government, Juan Bravo Murillo, strongly promoted the realisation of a modern service for the expanding city of Madrid[2] as a reply to the crescent needs of pure water for both domestic and industrial purposes. On the other hand Spain did not lead the scientific and technological knowledge, developed in industrialised countries in the same period, and the scientific and technological situation of the country was quite backward.

The Government, then, decided to politically support a project, which reflected and demonstrated the technical competence in public works already achieved by Spanish technicians.

The redaction of such an important project was entrusted to engineers of the *Cuerpo de caminos*, that was the most prestigious technical institution of the country.[3]

The engineers responsible of the project had a proved experience in previous public works, and in particular in the construction of canals, streets and ports in masonry: José Garcìa Otero, economic and optional Director of the work, but also architect and *inspector general* of the the *Cuerpo de caminos*; Lucio del Valle Arana, *Segundo director* of the Canal Isabel II, architect and *ingeniero jefe de segunda clase* (general Director of *Obras Pùblicas* from 1851); Juan de Ribera y Piferrer, *ingeniero jefe de segunda clase*; Eugenio Barròn Avignòn, and Constrantino Ardanaz *ingenieros primeros*.

All of them directed or participated to the redaction of many project for territory's infrastructures (retaining walls, earth dams, bridges, ports, etc.) all over Spain (Valencia, Sevilla, Madrid).

Some of them had also a solid career as professors of the *Esquela de Caminos Canales y Puertos*: Garcìa Otero taught *Principios de Arquitectura civil y Dibujo* (tercero curso); Lucio del Valle was firstly professor of *Geometria Descriptiva* (primer curso) and later on of *Geodesia*; finally Juan de Ribera taught *Arquitectura y Estereotomia* (segundo curso) at the same school.

The technology adopted was mainly cut-stone masonry, because of their perfect knowledge of stereotomy and of its application to civil architecture and public works.[4]

The experimental construction site at the Pontòn de la Oliva (1851–1858)

The Ceremony for the laying of the foundation stone of the masonry dam took place at the Ponton de la Oliva on 11th August 1851. The earth dam, that corresponds to the first section of the Canal Isabel II, would be inaugurated on 24th June 1858 (Fig. 2).

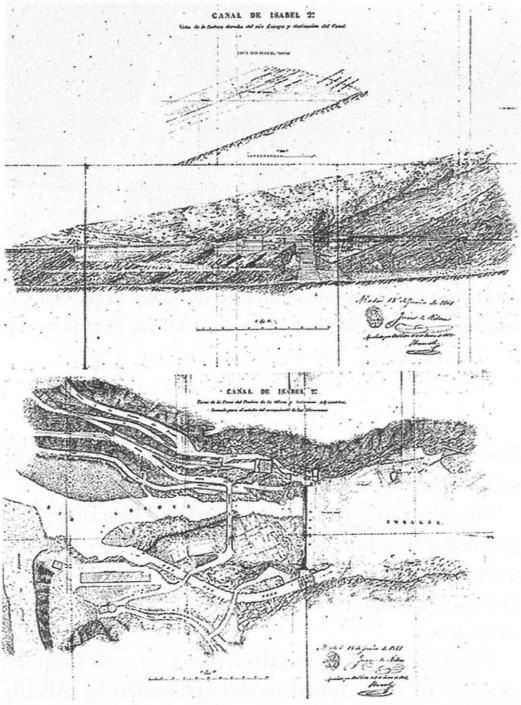


Figure 2
Plan and Frontal view of the earth dam and its surroundings buildings (1851). Archivo Central del Ministerio de Fomento. (supplied by J. J. Gonzales Reglero)

The site is 65 km away from Madrid, and is comprised in the administrative municipality of Patones (province of Madrid) and Uceda (province of Guadalajara) on the North of the capital.

This terrific natural site was chosen in August 1851 as starting point of the Canal Isabel II, that in a few years would conduct the water of the Lozoya river to Madrid. Lucio del Valle and Juan de Ribera were the engineers responsible for this section of the project. The labour was composed of 2000 prisoners, and 1500 workers (stone-cutters) for the different operation of the construction site.

The building yard of the dam includes some outlying service buildings: the prison barracks, the house of *compuertas*, the house of *mina de limpia*, covered with a flat-vault, the *casa del guarda*, the auxiliary buildings dedicated to iron-work, wood-work, stone work, mortar fabrication, and a brick furnace.

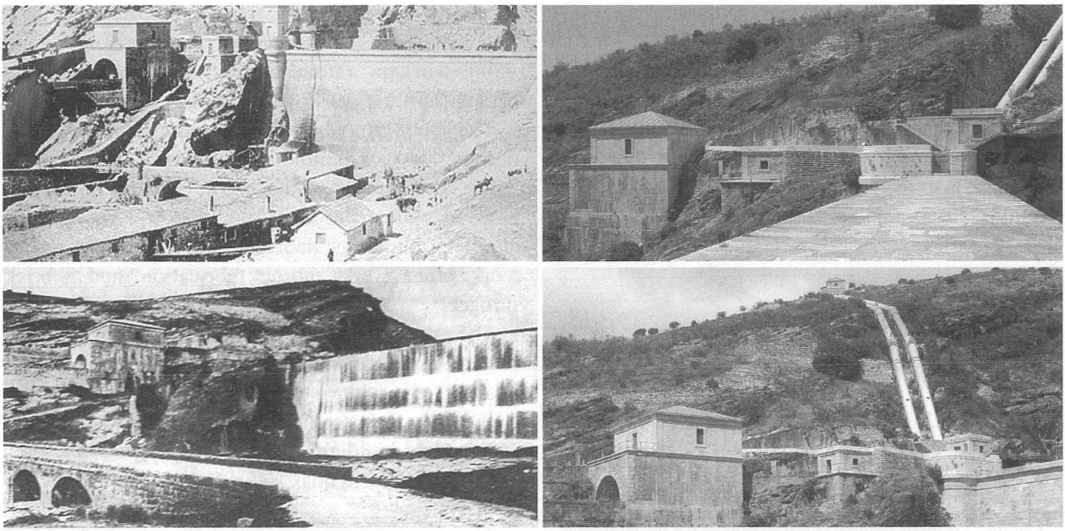
The stone employed for the construction of the dam and the annexed buildings was excavated in different quarries: the white stone of the dam derives from Redueña y Patones; the yellow limestone of the surrounding buildings, canals, and inspection points, was obtained from quarries on the two margins of the river.

The construction site at the Pontòn de la Oliva could be regarded as an experimental and scientific «laboratory» of construction. Firstly expert stone-cutters had to train prisoners to the art of stone-work: soon after they became a qualified labour that had to be employed in the following public works all around Spain. Secondly it could be possible that the construction site had been visited by scholars during the summer, in order to study practical applications of stereothomy: this is probably the reason why the project presents some stereotomical «games», and peculiar vaulted masonry systems, such as that of the *boveda plana* (flat vault) at the Casa de Mina de Limpia.

The masonry dam at the Pontòn de la Oliva was an impressive work for the period (Fig. 3–4–5–6): it could contain 3.000.000 m^3 of water, and has a coroner 70m long, and 27 m high; the cross section has a trapezium shape with the lower base of 51m width and the top of 6.5m. For the dam's construction the Administrative Council destined 4.174.659 reales.[5]

The flat-vaults at the Casa de Limpia: aesthetic quality of cisterns and inspection points' coverings

There great ability of the stone-cutters, who worked at the construction site, is proved not only by the terrific results obtained in the masonry dam, but also



Figures 3–4–5–6
Period picture of the construction site (supplied by J. J. Gonzales Reglero); The earth dam in activity (from Lopez berges, Emilio, Informes de la Construccion, n. 533–4, page 4); The context of the dam at the Pontòn de la Oliva, Photos by the author (May 2002)

in some minor examples and architectural details that could be found in the surrounding buildings.

It is the case of the small *boveda plana* that covers the *Casa de Mina de Limpia* (Fig. 7), that is one of the few realised examples of flat-vaults composed of serial elements with a polyhedric shape.[6]

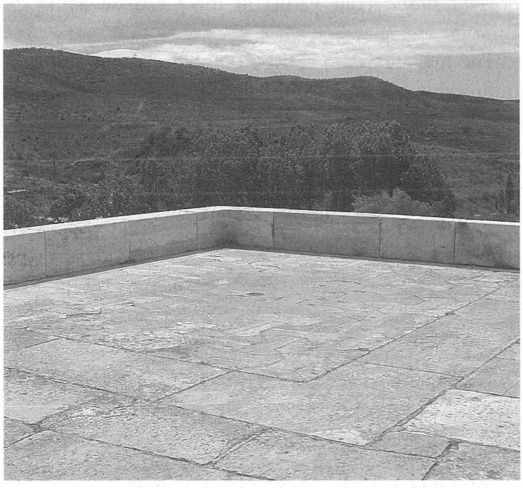


Figure 7
View of the boveda plana. Photo by the author (May 2002)

The flat vault, mainly indicated and described as a geometrical game, could be regarded as a direct quotation from A.F. Frezier's *Traité de Stéréotomie* (1737–39), one of the most important treatise of stereotomy.

The solutions designed by Frezier[7] started from the analysis of the original model elaborated by Abeille (1669?–1752?), described in Pl. 31 Fig. 37, and quoted the existence of two later solution by Sebastien Truchet (see Pl. 31, Fig. 38). He then describes his original new variants (see Pl. 31, Fig. 39 and Fig. 40) that could be considered as simplifications of the fine, and also complicated Truchet's solution,[8] in order to reduce and clarify the process of execution. These successive variants could be regarded not only as a geometrical game but mainly as an attempt to improve the static performances of the system.[8]

The model, realised probably for the first and last time at the Pontòn da la Oliva (Fig. 11), was designed by Lucio del Valle and/or Juan de Ribeira with a direct reference to Frezier's solution contained in Pl. 31, Fig. 39 (Frezier, 1737–39).

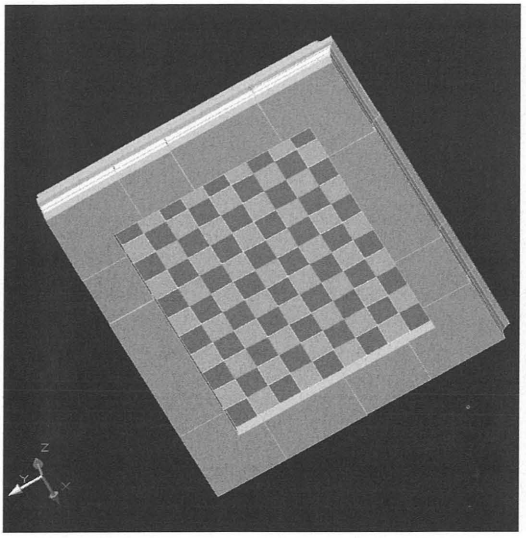


Figure 8
3D virtual Model of the flat-vault system. Drawing by the author (June 2002)

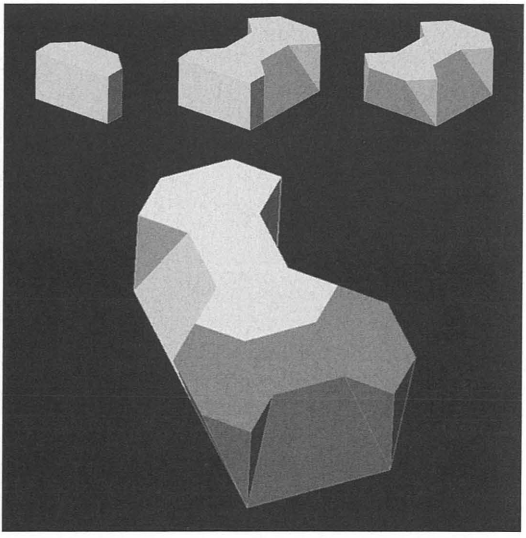


Figure 9
Abacus of flat-vault elements. Drawing by the author (June 2002)

The vaulted system and its supporting elements are modular and prevailingly symmetric (Fig. 8). Moreover the original units of measurement (Spanish feet) have been converted into metres[9] in order to better understand the proportioning process of the ashlars.

The small *boveda plana* covers a rectangular space (dimensions 310x380cm) which accommodates an inspection point. The overall dimensions of the flat system at the extrados are 397 cm × 328 cm, and its thickness is around 21 cm.

The form, geometry, proportions and dimensions of the elementary ashlars inform the entire composition:

— the square at the lower base is very small (around 35 cm side), and its composition designs an intrados' texture made of 9 per 11 squares;
— the top base is a polyline figure, and the circumscribed rectangle has overall dimensions of 35 × 51 cm (Fig. 9).

Frezier's rules for a correct execution of a flat-vault system, and its identical ashlars are respected. The process for their realisation is quite simple: too acute angles are avoided, because they constitute points of frailty and rupture; the projection of the bases and of the sides in order to obtain the *patrones/panneaux* that guide the execution are direct and do not require complicated geometrical constructions; the stone-cutting proceeds according to planar cuts.

The inclination of the sloping sides follows an angle of 67° (comprised between 45°-75° and 34'), and there is a very small utilisation of mortar so that the flat vault could be considered dry-assembled.

The solution is characterised by the continuity of the intrados and extrados, that offers a better resistance to the collapse (Fig. 10–11–12–13).

There are also interesting constructive solutions adopted for contrasting the horizontal trust of the system that can hardly be recognised from the intrados: the L shaped massive blocks in correspondence of each corner (Fig. 14–15–16–17), that are replicated with few variations in the elements that compose the parastas of the closing walls, creates a chain mechanism that avoid the collapse.

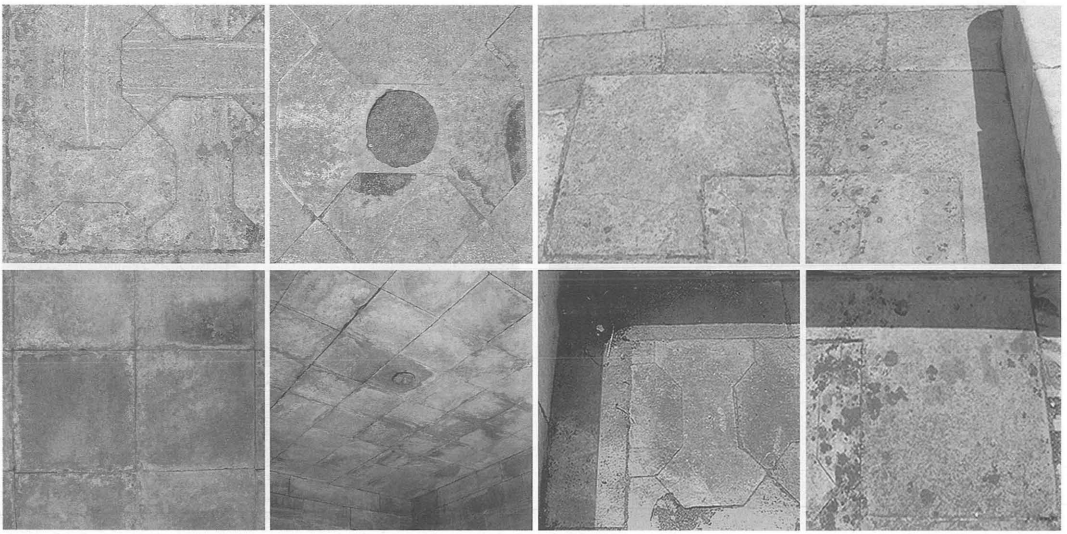


Figure 10–11–12–13
Details of the boveda plana. Photo by the author (May 2002)

Figure 14–15–16–17
Details of the boveda plana L-shaped corner blocks. Photo by the author (May 2002)

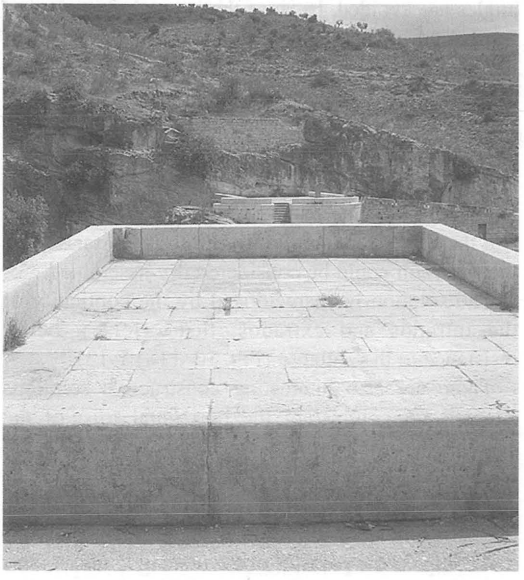


Figure 18
View of the extrados at the Casa del Guarda. Photo by the author (May 2002)

The hypothesis of reconstruction of the flat-vault at the Casa del Guarda: aesthetic quality, tectonic knots, stereotomy, and dry-assembly methods for updated «flat-vault» systems

In fifties some restoration works interested the earth dam and its surrounding buildings. In this occasion the building destined to the *Casa del Guarda* was deeply modified with the demolition of the rooms at the first floor and the substitution of the intermediate floor with a reinforced concrete structure (Fig. 18).

The analysis of the archives' data (original project: plans, sections and frontal views; period pictures, etc.) and the presence of recurring constructive and architectural details (the same L shaped massive blocks in correspondence of each corner, identical parastas of the closing walls for the chain mechanism, etc.) suggest the existence of a second flat-vault system corresponding to the intermediate floor, now demolished (Fig. 19–20–21–22).

The hypothesis of reconstruction followed some preliminary conditions:

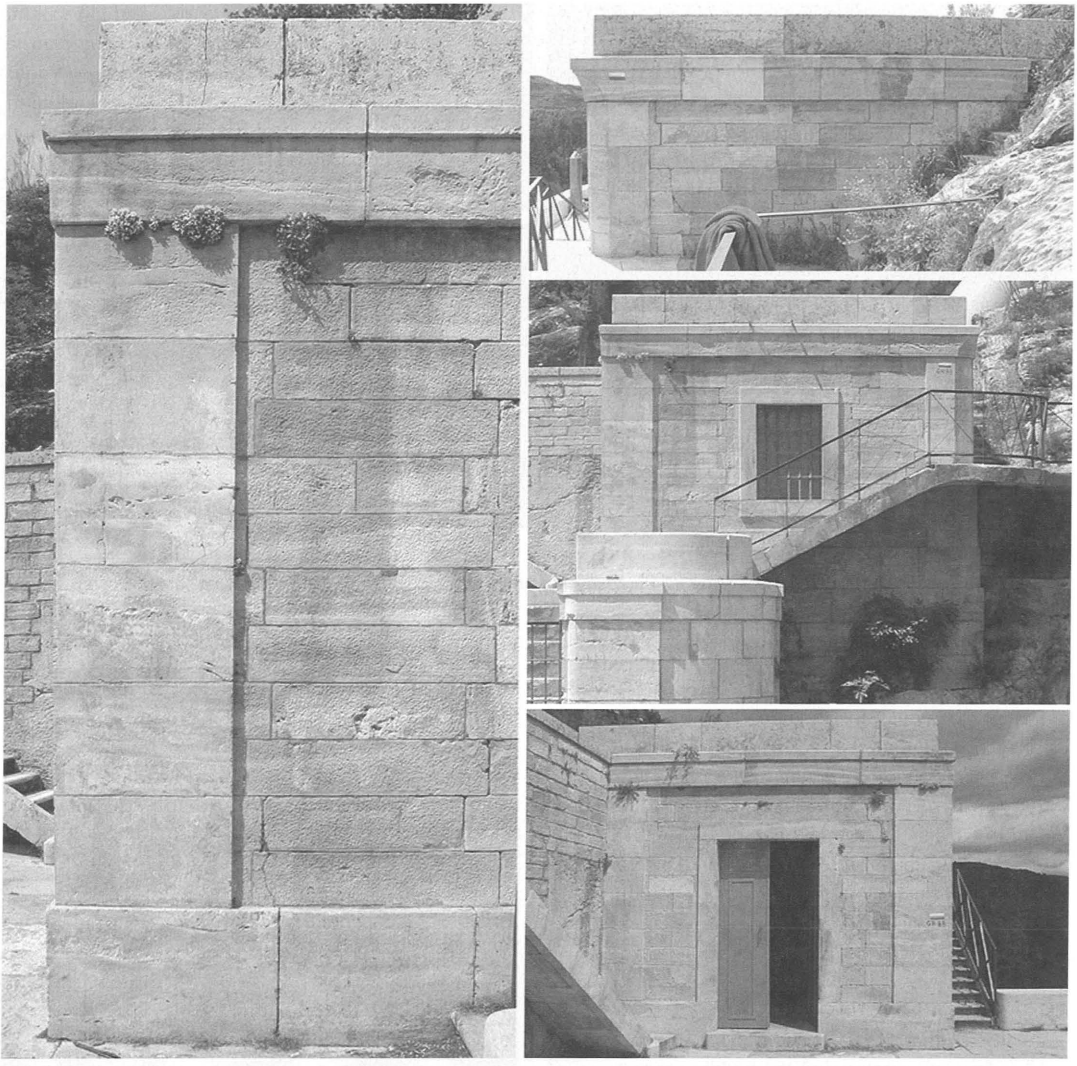


Figure 19–20–21–22
Details of the supporting structure. Photo by the author (May 2002)

— among the different possible flat-vault solutions it was selected a lacunar ceiling, obtained overturning the Abeille's original solution;
— the inclination of the sloping sides had to follow an angle of around 60°;
— the thickness of the system has to be 23.22 cm (10 *pulgadas*);
— the overall dimensions of the intrados were 304,20 cm (11 *piez*) × 373,84 cm (14 *piez* and 4 *pulgadas*);
— the overall dimensions of the extrados were 348,30 cm (12 *piez* and 6 *pulgadas*) × 417,96 cm (15 *piez*);
— the support tapering was around 22 cm (9 *pulgadas*).

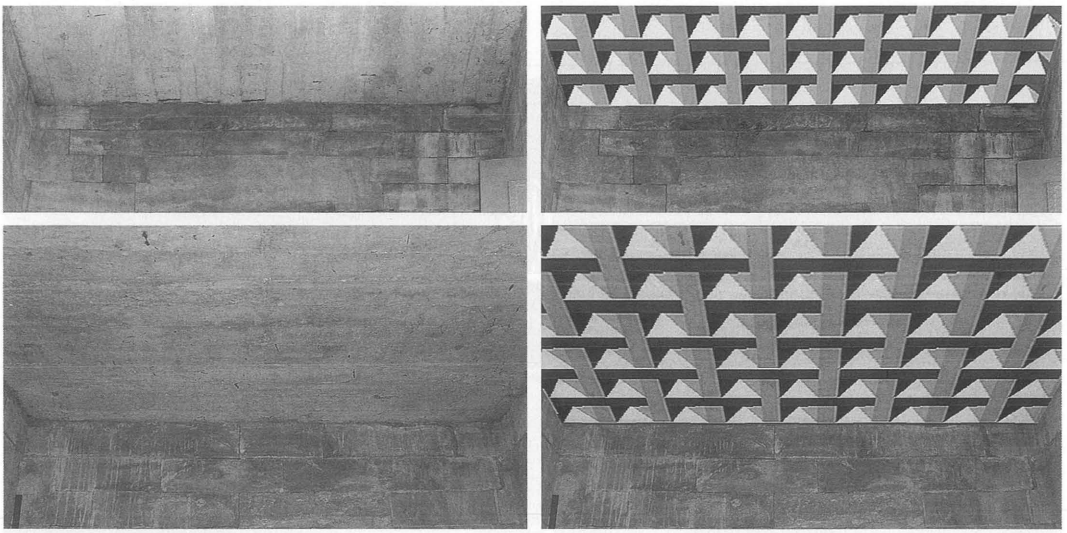


Figure 23–24–25–26
View of the intrados at the Casa del Guarda. Photo by the author (May 2002) and photomontage of the reconstructive hypothesis

The obtained flat-vault system is a rectangle with a extrados made of 12 per 10 squares. The dimensions of the serial element are the following:

— the lower base is a rectangle 58,05 cm × 11,61 cm (2 *piez* × 5 *pulgadas*);
— the top base is a square 34, 83 × 34,83 (15 *pulgadas* × 15 *pulgadas*) with the same dimensions of the nearest realised example ashlars' intrados;
— the sloping sides, that follow an angle of 56°, are conformed with a mortise joint (tectonic knot) that improves the friction among the elements, contrasting the bedding thrust.

The Abeille's problem of the pyramidal holes extrados (that have to be filled in order to obtain a trampling layer) is solved by the continuous square plot. However the preference for this architectural scheme, and for the aesthetic quality of such a lacunar ceiling (Fig. 23–24–25–26) involved the solution of important structural and technological problems.[10]

Firstly the discontinuity of the intrados constitute a lack of resistance to the collapse, only partially solved by the employ of mortise joints. Secondly the contemporary structural requirements (static and ductility safety) prevent the use of un-reinforced pushing structures (Fig. 27).

For these reasons the reconstruction hypothesis provides an flat-system improved with

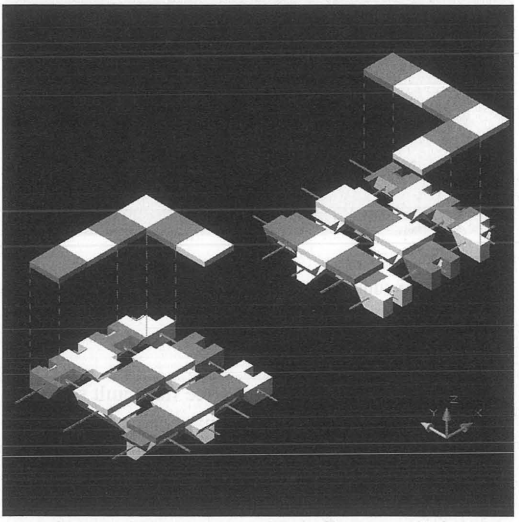


Figure 27
Abacus of reconstructed flat-vault elements. Drawing by the author (May 2002)

reinforcements: the tie-beams, positioned in correspondence of the block central axes in both directions, represent a security stitch against plastic deformations and frail rupture of the flat vault. Moreover the special blocks in correspondence of each side of the overall structure receive the tie-beams with their anchor slabs, positioned in the corresponding cavities. The application of a pretension to the tie-beams involves some advantages in the management of the restoration site: the entire system, in fact, could be pre-assembled and set on the existent structure. The necessary contrast to the horizontal actions will be provided by both the tie-beams and the existent monolithic L–shaped blocks at each corner of the system.

Critical reflections on the cad/cam processes' application to the architectural elements production

The twenteenth-century generalised lack of experimentation in load-bearing stone construction has determined, not only a suspicious approach to the traditional repertory of vaulted systems (i.e. vaults, trompes, etc.), but also a great difficulty in finding expert stone-cutters for their execution.

Recently the on-going research field established by Prof. Claudio D'Amato at the Politecnico di Bari, has experimentally proved the potentiality of informatics' technologies (i.e. cad-cam processes) for the revaluation of the Mediterranean constructive tradition, specifying the application of cad-cam process to the realization of stone architectural elements.[11]

The elaboration of the reconstructive hypothesis for the flat-vault could be regarded as a critical reflection on the the traditional relationship idea-construction, expressed in the stereotomy treatises' repertory. On the one hand the 3D model and render images have been elaborated in order to analyse the texture of the stone system in the light of the ashlars' execution with CNC machines. On the other hand the 3D model could be easily imported by many structural engineers' programs for the description of the structural behaviour. It also provide a clear differentiation of supporting and supported elements.

It could also be used for the elaboration of animations, that illustrate concepts that are not easy to depict by means of static images, and with the purpose of offering an important contribution to the comprehension of the construction and assembly process of the traditional stone systems analysed. They both exemplify the different phases for the ashlars' traditional/electronic execution to non-expert stone-cutters and architects, and clarify the system's construction process.

There are several advantages in using cad-cam processes for the realization of the flat-vault ashlars (Fig. 28):

— executive precision; speedness of the realization process in comparison with traditional stone-cutting; rationalization and repetibility of cutting and finishing processes, in the light of a dry-assembly;
— predominance of «border processes» (cutting, bordering, drilling, etc.) towards «shape processes» (mainly used for the realisation of no planar surfaces), that implies a short time in the elaboration of the CN-file to be used by the CNC machining centre;
— elements' dimensions and proportions compatible with almost all the more common CNC machining centres at our disposal.

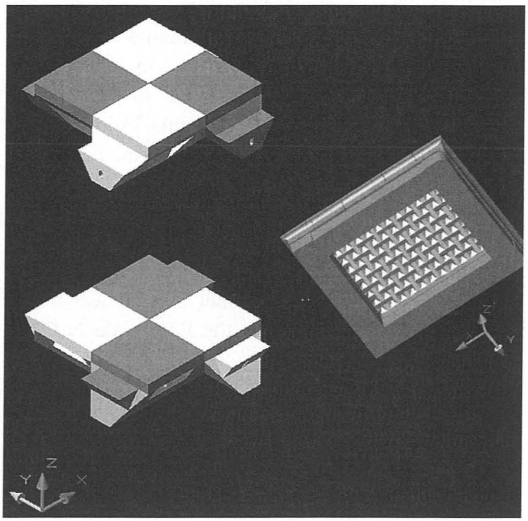


Figure 28
3D virtual Model of the reconstructive hypothesis: comparative analysis of mortise joints solutions. Drawing by the author (May 2002)

The employ of a CNC machining centre implies an enlargement of the expressive possibilities: firstly exclusive solutions (i.e. Truchet's one) could be easily obtained with a CNC machine; secondly the cad-cam process could be elaborated for both the ashlars' positive (i.e. the traditional natural cut-stone element) and their negative (i.e. their formwork in steel, polystyrene, etc.).

This opens new horizons for the architectural experimentation, in terms of use of different materials (such as reconstructed stone), and definition of new methodologies a high qualified prefabrication.

Acknowledgements

This paper summarises, in some aspects, the contents of an on-going research project titled «Typological and constructive updating of vaulted systems for the contemporary project in stone» (G. Uva; E. de Nichilo, A. Di Roma, G. Fallacara). The project has gained in 2002 MIUR Young Researcher funds and is being carried out at the School of Architecture of the Politecnico di Bari. One of the distinctive characteristics of the School resides in the research line on stone construction, under both traditional aspects and needs for its technological updating.

This is the general frame that has strongly supported the intensive and experimental work I have carried out in close collaboration with Giuseppina Uva. I am very much debited to Professors C. D'Amato Guerrieri and M. Mezzina, Politecnico di Bari, for their precious suggestions. Prof. E. Rabasa Diaz, offered his extremely important comments, and enabled me to connect this study with current work on the history and theory of stereotomy. Finally I would like to express my gratitude to Juan J. Gonzales Reglero, Fundaciòn Canal Isabel II, who was a true support during the survey at the Pontòn de la Oliva (May 2002). He not only offered his technical suggestions, but also was very generous in putting his facilities and the material of the archive of the Fundacion at my disposal.

Notes

1. The Council was instituted by the Government headed by Juan Bravo Murillo on 18th June 1851 with a Real Decreto during the kingdom of Queen Isabel II and her husband King Francisco de Asis. The structure of the Council included three representatives of the Government: Juan Fernandez de Cordoba, XIV conde de Sàstago, who was also the President of the Council; Josè Solano Mata-Linares, marques de Socorro and deputy-President of the *Real Academia de Ciencias Exactas, Fìsicas y Naturales*; and Manuel Cantero, member of the Government in the Banco Español de San Fernando.
2. The *Cuerpo de Ingenieros de Caminos, Canales y Puertos* included technicians (soldiers and engineers) trained to the *Real Casa de Caballeros Pajes* and later on to the *Esquela de Caminos Canales y Puertos* (re-opened for the third time in Madrid in 1834). The Institution had a hierarchical structure: at the top there was a very limited number of *inspectores generales*, followed by *ingenieros jefes de primera clase, ingenieros jefes de segunda clase, ingenieros primeros* and *segundos*.
3. An important aspect to be considered is the role that stereotomy had in the nineteenth-century engineers' training. Different application of stereotomy were taught in many courses at the universities, and the preliminary condition to follow them was the perfect knowledge of French. The French and Spanish treatises of stereotomy and military art, in fact, were used as textbooks. The engineers of the Canal had a great knowledge of these treatises and contained constructive models, proved by the adoption of many solution in the canal construction.
4. It is important to compare the Spanish situation with the coeval French and Italian ones. In Nineteenth-century the generalised request for new technical and specialised competences had two important, and contrasting consequences. On the one hand the need and the preference for practical aspects of the discipline explained the abandonment of the *treatise* in favour of the *manual*, that contained ready-to-use solutions. On the other hand, the strictly geometrical experimentation of some authors (i.e. Monge) led to the elaboration of stereotomical abstract models that lost their reference to the constructive reality. On the role and predominance of the «Art of building» in the French and Italian architects/engineers' training see: RAMAZZOTTI, Luigi, *L'edilizia e la regola. Manuali nella Francia dell'Ottocento,* Edizioni Kappa, Roma 1984; and SAKAROVITCH, Jöel, *Épures d'architecture: De la coupe des pierres à la géométrie descriptive XVI-XIX siecles*, Basilea, Birkhäuser, 1998.
5. Cfr. Gonzales Reglero, J. J., *1851. La creaciòn del Canal de Isabel II. El Marco Historico*, Volume II, pp. 203–234, Fundaciòn del Canal de Isabel II, Madrid, 2001.

6. The small flat-vault at the Pontòn de la Oliva is the study-case of the PhD thesis the author is carrying out, and titled *Vaulted and domed architectural systems in dry-cut stone in Spain. Sixteenth-Nineteenth centuries. Sequences, tectonic knots and stereotomical techniques in comparison*, Thesis supervisors: Prof. C. D'Amato, Politecnico di Bari Dipartimento ICAR - Prof. E. Rabasa Dìaz, E.T.S. de Arquitectura de Madrid, Departamento de Ideacion grafica arquitectonica, PhD Course in Progettazione Architettonica, Università degli Studi di Palermo, ciclo XIV. From the seventeenth century a formal and stylistic research field on flat-vaults had been developed in a limited number of French and Spanish treatises as evolution of the traditional vaulted systems. It is possible to divide the different flat-vault systems (*voute plate/bòveda plana*) in two great families: the flat-vaults with converging cuneiform ashlars (such as the one realised by Juan de Herrera at the S. Lorenzo's Monastery, Escorial 1575); and flat-vaults composed of serial elements with a polyhedric shape. The solution realised belongs to this second family: its survey, conducted by E. de Nichilo, G. Uva and G. Fallacara in May 2002, has highlighted the presence of many interesting stereotomical typical details, and the differences with the abstract model described in the treatises.
7. Frezier A. F., *Traité de Stéréotomie*,[1737–39] 1980, pp. 68–79. The Abeille's original solution was presented at the *Academie des Sciences* in 1699, and edited in *Machines et inventions approuvées par l'Academie Royale des Sciences*, Tom. 1 pp. 159, 1735). The serial elements had a polyhedric shape: the lower base is a square, the top base is a rectangle, and the sloping sides are trapeziums. It is possible to assembly the ashlars, alternating the directions of the placed pieces and obtaining the covering of a square space. The texture of the intrados has a square plot while the extrados presents pyramidal holes that have to be filled in order to obtain a trampling layer. J. M. Perouse de Montclos, in *L'architecture a la francaise,* does not mention any realised examples of the Abeille's solution or its variants in France. E. Rabasa, in *Forma y construcciòn en piedra*, has documented one more small example of a flat-vault in Spain: the *boveda plana* of the Northern tower of Lugo Cathedral, designed by Julian Sanchez Bort (1727–1785). Here the Abeille's system is poured and adapted to a rectangular plan. The central part was reconstructed in 1879.
8. A comparative analysis of the different flat-vault solutions contained in Frezier's treatise, with reference to both geometrical characteristics and structural behaviour, was developed by the author and G. Uva, within the Research Unit of the Politecnico di Bari of the MIUR ex-40% funded research *The typological and constructive reform of the Mediterranean house* 1999–2001, (national and local coordinator: Prof. C. D'Amato, Dipartimento ICAR, Politecnico di Bari).
9. The conversion units utilised are:
   1 *piez* (Spanish foot) = 27,863 cm
   1 *pulgada* = 2,322 cm
   1 *piez* = 12 *pulgadas*
   Cfr. Gonzales Reglero, J. J., *1851. La creaciòn del Canal de Isabel II. El Marco Historico*, Volume II, pp. 225–226, Fundaciòn del Canal de Isabel II, Madrid, 2001.
10. For the *boveda plana* structural mechanism see:
    — E. de Nichilo, G. Uva, «Hydraulics and Stereotomy: the Experimental Construction Site at the Pontòn de la Oliva (Spain, 1851–1858). Stone Techniques for the Nineteenth-century Territory's Infrastructures» (pp. 61–68) PART II (by Giuseppina Uva): *Development of structural technical solutions for the* out-of-plane *strength of cut-stone masonry.* Proceedings of the International Conference *Landscapes of Water. History, Innovation and Sustainable Design*, Monopoli 26–29 September 2002, Corcelli Editore, Bari 2002;
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11. Since the beginning of Nineteenths Prof. Claudio D'Amato Guerrieri heads a more general but complex project, on the updating of traditional techniques of construction using cad-cam processes. The first impressive research result of cad-cam application to architectural elements' production, was the 9/A capital replica of Apollo Epicurius' Temple at Bassai, made of Carrara marble (120x60x60 cm) using numerically controlled machines (CNC machines), presented at 35° Veronafiere MARMOMACC in 2000.

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Buildings of beginning of '900 between tradition and innovation: From the art of building in the treatises to building practices of handbooks

G. De Tommasi
F. Fatiguso

Research faces the study of evolution process affecting building of first decades of XX century; such building where characterised by transition from old and reliable construction techniques —the *art of building*, codified in theoretical treatises between humanistic and scientific knowledge— to new and experimental, for that age, materials and building systems —explained in friendly handbooks aimed to divulgation of technical innovations and to practice education of professionals, master builders and students.

The age is marked by a wide interest toward new materials and new construction techniques culture for which there is a sure trust in their usability and durability in the time. For these reasons, a gradual and continuous process of contemporary use and/or substitution of traditional construction materials and techniques with modern ones took place (from use of simple and cast iron to more flexible concrete, iron reinforced or not); such process progressively involved even common buildings such as residential ones when such materials and techniques went into market marked by features of higher economy in terms of time and costs.

In particular, the research highlights material-technical-technological evolution path generated by gradual introduction of new materials and substitution of single elements of building first —flat arches, arches and ceilings with iron and/or concrete/tile structures—, then of whole parts —stairs, vertical backbone and transversal frames with beams and pillars in reinforced concrete— and finally of whole bearing masonry box.

In this way it is possible to define, as much to a level of building complex in its whole as to a level of single elements and/or subsystems, material, technical, technological features of the «new» building type which has long been neglected and today in the focus of interests and studies, for historical and architectural aspects, but still not much analysed under technological and structural profile.

Preface

Buildings between the end of XIX and beginning of XX century are characterised by transition from traditional materials and old and well-established construction techniques to new materials and to modern techniques and technologies. There is the presence of traditional and modern culture which, within the enthusiasm of reached and reachable results look with sure and absolute trust at innovative techniques and materials, at their usability, at their durability in time.

All of this let operator require a multidisciplinary knowledge and continuous updating which is supported by spreading of a technical press made of manuals and friendly handbooks of popular and practical features.

This study faces evolutional process which affects construction, from gradual introduction of new

materials and substitution of single elements of buildings —flat arches, arches and ceilings of iron and/or brick-concrete structure— up to construction of new building with reinforced concrete structure.

Through reading and analysing of technical information related to construction elements contained in manuals, it is intended to analyse historical, technical, typological evolution of buildings, taking into account specific constructive aspects and defining material-technological-structural features.

The aim is systemising of knowledge as a preparatory stage to analyses of specific decay processes of such building heritage and to definition of methodologies aimed to their conservation.

With present work-in-progress a first path is traced in order to define modality and operative processes limited to singular cases but extendible, in the methodology, to whole building complex.

Construction tradition in Treatises

Up to XVIII century, building is founded both on a consolidated technical knowledge transmitted from generation to generation and on generics theoretical aspects of Architecture expressed within Treatises.

Traditional building practice, technical procedure of an architecture intended as mechanical art, is then originated and transmitted by architects and workers: local construction traditions, quality of materials of the territory and skill of workers condition and have influence on characters.

Treatises mainly concentrate on theorisations of general and cultural kind, both for strictly didactical aspects of transmission of technical knowledge and for larger concepts of encyclopaedically characters. In such view the attention, from Alberti to Palladio, from Vignola to Serlio, is mainly located upon basic «rules» for designing and architectural composition of building, rather than upon technical prescriptions for building it. Even when the intention is clearly practical and popular, as in case of Rusconi Treatise, construction practice is described and illustrated in an ideal vision of building reality and human work founded upon philosophical principles.

Respect of fundamental values of symmetry, order, precision in execution and quality of materials allows producing the beauty and the harmony: practical realisation is instead committed to respect of codes and consolidated habits which constitutes that large technical-cultural heritage which is named as «Best Practice Codes». Such Codes, within unitary conception of theory and practice which is proper of humanistic culture, are considered the fundament of ideological premises of Architecture and they are the shared patrimony of all operators of building process.

With Age of Enlightenment and French Rationalism, a scientific approach to building begins to establish, with attention to single building operations which lead to realisation of building. Treatises start to lose part of their strong theoretical connotation and the interest to the object in its whole, thus giving more consideration to practices and construction modalities: the aim of treatises turns into «let known arts improve and let ancient lost arts be retrieved» (Diderot and D'Alembert 1772), while spreading of rationalist thesis implies establishing of «mathematical and physical principles applied to different art operations» (Rondelet 1802).

Treatises are then affected by an evolution originated from confront between the Art of Building, the Construction as a Science and the Academic Beauty, thus trying to find an unifying element in the recourse to scientific and mathematical method. All of this progressively changes contents: if building is a science then description of techniques and construction details is necessary.

A clear example is given by Rondelet Treatise itself; in it, the interest in the scientific problem of definition of criteria for determination of building stability, for comprehension of mechanical behaviour of structures and for optimal determination of geometrical dimensions of architectural and structural elements, is showed with scientific strictness through illustration of historical experiences and recent exemplar cases, but also through consolidated practises.

Building transformation between XIX and XX century

Starting from Industrial revolution, Technical-Scientific turmoil involves all knowledge sectors without distinctions, even included consolidated construction practise, thus provoking a more and more rapid and capillary spreading of produced materials, together with knowledge and experience done.

In Construction field, the unavoidable transferring of knowledge between different sectors of production determines the passage from a «craft kind of knowledge» to an «industrial type» following a process which leads to separation between ideation moment of design and is realisation moment.

Transformations, which Industrial Revolution has provoked upon construction process, are well known. Without recalling them, it has to be highlighted that such mutations thrown into confusion construction tradition under three fundamental aspects.

As first, materials and construction methods change: new materials such as cast iron, iron, glass, new kind of bricks, and, moreover, cements and reinforced concrete are produced; traditional materials are craft in a more rational way and distributed more easily and cheaply; scientific progress allow to measure materials resistance and to put them in work in a cheaper way; site equipments improve and construction machine use is spread; developments of descriptive geometry allow to represent in an univocal way all aspects of construction. This, for example, determines gradual substitution of wooden beams with iron ones, in a first stage as main bearing structures and then as secondary together with spreading of use of brick elements (mechanical bored bricks). Or again, the substitution of internal bearing masonries with cast iron columns took place in order to obtain less bulk and more flexibility.

As second, new building types appear, in order to satisfy needs of Industrial Society —plants, warehouses, depots, markets and slaughterhouses, train stations, rails, and even cheap houses— and quantities increase due to rising need of infrastructures for the territory.

As third, a new sense of time is developed, in which buildings are something which is not to be considered unchangeable and «definitive», but only the answer to a contingent need.

All of this also changes common construction, when rapidly increases introduction of «new» materials within usual building procedures, thus provoking remarkable mutations in Architecture, as a global fact and equilibrated result of different components. Practically, under pressure of industrial progress a difference increased between traditional construction theory and new building practice, which means between Architect figure which was linked to theorisation of Beauty (and then progressively strained to decorator role) and Engineer figure which was synonymous of progress and concreteness (and apparently more ready to satisfy contractor's and production world). Roles and competence of building process operators turn and even scholastic system transformed itself: progressively, the specificity of Architects and Engineers characterises itself in a not uniform manner, intermediate classes were born of experts and master builders with responsibility of site and execution of buildings, applicative schools of engineering were born.

Such evolutional process which affects construction determines spreading and expanding of technical press: near treatises and their new editions, magazines start to appear and strictly educative books are supported by operative and popular handbooks.

Several are the reasons at the base of different publications: firstly, the need for documenting conditions of economical development and for receiving technical and social problems of nineteenth-century town; as second, industrialisation which requires more and more a scientific and technical culture (which put itself on a culture now seen as abstract, which had been mainly humanistic and seen at the base of knowledge) conformable to indications of new positivism.

Further reason is the need for an updated and deep knowledge of new materials and technologies, both for their production and their placing on site: fast progresses of those years in all sectors request to different actors of construction process, in short time, a multidisciplinary knowledge and technical competence and capacity of a continuous updating. An example of this, it is the publication, in 1888, of first volume of «Dictionary of Civil, Mechanical, Military and Naval engineering» from Brine and Spon; the book contained all new terms of technical nomenclature and it represented the update of «Encyclopedie» from Diderot and D'Alembert. Another case is represented by Curioni's Manual (Curioni 1868), which was published in six volumes from 1865 to 1870 when in 1873 already saw an appendix for its update; the updating opera went on up to 1893 when sixth appendix was published after his death.

At last, the already said transformation of roles and competences of operators of building process determines spreading of a press whose character was

extremely popular, with schemes, handbooks and illustrations as more documentary was possible. As an example, in Italy, numerous manuals from Hoepli, Vallardi, UTET published in those years, were the answer to a spread need for education of a new managing and intermediate class that had in common their technical education.

That is why manuals collect available documentation in construction field, with the aim to provide young graduated and professional with a large knowledge of practical notions, in a way to let them be expert from building practice after they had studied their theories. Generally, most faced themes are the ones related to material and production evolution, to construction methods most commonly approved or most common in practice, to codified practices and to innovations on which the consent was going to be produced, to birth and evolution of residential problem, to the whole of code and legislative tools, to building types and related hygienically-sanitary problems.

Building between Tradition and Innovation

Study of technical press allow to trace in a precise way the historical evolution of building in the mentioned period, characterised by gradual but continuous supporting process and/or substitution of materials and traditional construction techniques with modern ones. In other words, manuals define the state of the art in construction: detailed description of executive construction techniques, of operations and site equipments, of available materials, allow the reconstruction of building process organisation, of construction processes and of realisation modality. In particular, the analyses of technical information related to construction elements contained in manual literature of 1850–1940 period allows precise definition of material, typological, constructive, technological and structural characters of building in first decades of XX century, as much at a general level as at a building complex, single sub-systems and construction elements level.

Contemporaneous and parallel existence of traditional aspects together with innovative ones determines buildings based upon general theorisation from one side and upon practice and direct on-site testing from the other. Building practice lies, however, on a scientific approach in which operator knows theoretical aspects of materials and innovative techniques, experiences done and obtained results, indication and practical notions for their use. Such approach is already present within the articulation of exposition of subjects from Curioni's Manual (Curioni 1868).

Technical knowledge is often limited to a minimum level which allows the comprehension of new solutions and proposed technologies. An example is realised by chapters on civil plants from Donghi's Architect Manual (Donghi 1905), in which practical and popular aim imposes, even in a large text, to dedicate only short notions on scientific and technical principles at their base.

Fast spreading process of new materials and techniques determines an increase of the complexity level in building, with a progressive dismissal of traditional universal and whole vision of the building: building complex starts to be resolved in its main components of which different typological and technical possible solutions are studied together with sequence of construction phases and putting on site of materials and construction elements. This is easily findable in the sequence of graphical schemes within Copperi-Musso's Manual (Copperi and Musso 1870) which give exemplifications in a simple and intuitive way, even with recourse to axonometric views and sections in order to ease comprehension of construction techniques, a complex building technique, from the big scale to details of windows and door hardware.

A building technique, articulated in general components take place; each element is untied from particular applications and/or local uses in order to let the operator use them in most opportune ways that means according to needs deriving from particular exigency. Such fundamental concept pervades Breymann's Manual (Breymann 1895), where, as an example, in parallel, notions for structural calculations with new materials (even with complex formulas) are described as much as schemes for predimensioning of elements (i.e. iron beams or slabs), thus anticipating what is a feature of contemporary technical documentation.

This is then the evolution toward buildings realised by assembling of technical solutions pre-constituted or ideals, optimisation of shape/type —construction/material relation, to adequate or not to particular

context. In this view Manuals become sort of referring «Catalogues» for construction operators. An example is Formenti's Manual (Formenti 1893), in which meticulousness of representation and technical particulars showed in numerous graphical schemes seem to testimony solidity and quality of construction systems, moreover of new patents or mixed systems with new materials.

Buildings of first decades of XX century, then, intermediate between pre-modern masonry construction and «modern» reinforced concrete ones, seem to be characterised by complex and articulated construction systems in which there is a co-presence of elements and materials referable to traditional building coded in «Best Practice» —vertical bearing structures made of stone masonries and/or bricks and ceilings made of stone vaults and/or bricks and/or wooden slabs— and of materials and elements from Industrial Revolution —new materials such as iron and concrete, ceilings made of wood and iron, of iron and bricks, of reinforced concrete, and vertical elements made of cast iron columns, beams and pillars in reinforced concrete.

In this paper it is considered to be important to underline two exemplificative aspects of evolutional path of buildings in those years: on one side the appearance of technological solutions for finishing of external surfaces of masonry by use of «artificial» stones (mainly craft and empiric experience realised outside theorisation of Academy), on the other fast substitution of wood with reinforced concrete in realisation of slabs (process happened, on the contrary, with direct involvement of Academy and industrial world).

A NEW BASE-MATERIAL: «ARTIFICIAL» STONE

Desired and searched from past Architects, «artificial» stone finds, in the experimental fervour of considered period, its practical realisation in concrete applications, the «new» material at its best: its sudden birth, marvellous and apparently not thwarted spreading and us much fast disappearing is then exemplificative of fast evolutional processes of beginning of nineteenth century buildings.

Introduction of Portland cement at beginning of '800 and consequential fast progress of studies and production of different types allow placing in the market of a new base-material, an «artificial» stone made similar to natural and more expensive ones, often difficult to get due to distance of caves and/or difficulty of their extraction. Artificial stone, letting the designer free from bounding related to geographical placement an to displacement on the territory of natural elements, but also, and moreover, appearing not to be subject to precariousness of being natural with consequent lack of homogeneity and complication of manufacturing, becomes symbol of new progress performed by industrial society.

Then, during first decades of XX century a new technology develops which affects external surfaces of masonries, but also stairs, pavements, internal decorations, parapets and balconies, brackets and labels in a vertiginous process mainly founded upon products whose definition was the result of experiences performed with craft criteria but with proto-industrial production developments. It is an example, in Italy, fast development of Ghilardi Company, the first one to start cement handmade products: from first craft workshop on 1876 in Bergamo, in which production takes place by use of machines invented and optimised by Ing. Ghilardi himself, the company gets to four plants in Bergamo, Milano, Bari and Palermo in 1886.

Evident were the advantages of the new material: handmade of artificial stone appears as solid as marble, unalterable along use and as cheap as bricks. In pavement case, as an example, it has to be underlined their elegance (due to variety of sketches and colours) and moreover their healthiness (as they don't generate dust and don't adsorb humidity).

Evolution of artificial stone, very fast but also of a short duration, basically went on without direct involvement of Academy, left at margins of productive process, all founded upon empiricism.

Fast and definitive establishment of modern materials and techniques determines the end of short success stage of such technologies: the suddenly disappear together with men that produced them and with knowledge mainly derived from their experience.

FROM WOOD TO REINFORCED CONCRETE: RAPID EVOLUTION OF FLOORS

Evolutional path of building of beginning of nineteenth century starts, as said, with progressive introduction of

«modern» elements and materials in «traditional» techniques and technologies of building: substitution of stone natural elements with others of artificial kind, but moreover of structural elements (firstly flat arches, arches, vaults and wooden floors) with others made of iron, reinforced concrete and brick-concrete.

A demonstration is represented by introduction of iron reinforcing systems of floor wooden beams, used in case of excessive length and/or loads. Reinforcing systems documented in different Manuals (i.e. Cantalupi's Manual (Cantalupi 1862)) are a multitude but the on «commonly adopted» (so defined by Formenti (Formenti 1893)) consists in connecting under wooden beam one or two punchers, respectively at middle or at the same distance from the middle point, and in placing under these a iron tie which is blocked at its edges to beam's extremities in order to let this one, with its load, pull ties in tension; these avoid inflexion of beam with their resistance.

Iron frames already appear during middle of '800, even if their use is defined by Curioni (Curioni 1868) still «strictly limited» in Italy. Introduction of this new construction element, iron beam, is possible according to development of iron industry with consequential production of profiles made for specific use, to need for reducing risks provoked by fire, to extraordinary increase of cost of wood happened along middle of XIX century due to extensive use of it in railway construction, to possibility for reducing height of frames. Initially the use of iron bearing floors spread itself completed firstly by wooden slabs and then by little vaults made of natural or artificial blocks, by hollow clay block and by special bricks the «hollow flat blocks».

A multitude technological solutions of mixed floors in wood and iron, moreover with reference to connection between iron beams and wooden rafters (or slabs) and evident inconvenient determined by low compatibility between wood and iron: «And really, if we have the connection of iron elements with wooden beams by use of bolts which go across wood it is an easy probability that wood humidity generates rust on connecting iron». (Breymann 1895).

First example of mixed floors, made of iron beams and bricks, is represented within Curioni's Manual (Curioni 1868), but it is in 1892 that first patent for iron beams and artificial plane slabs was obtained: they were Klein floors made of iron beams and slabs made of bricks and iron stripes. Figure 1, Figure 2.

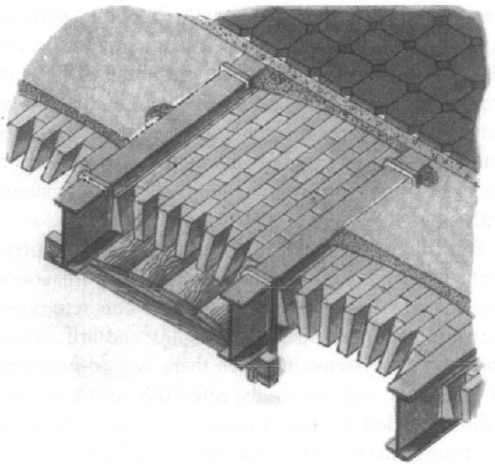


Figure 1
An example of floor made of iron I beams and little vaults in bricks (Misuraca, Albertini and Boldi 1900)

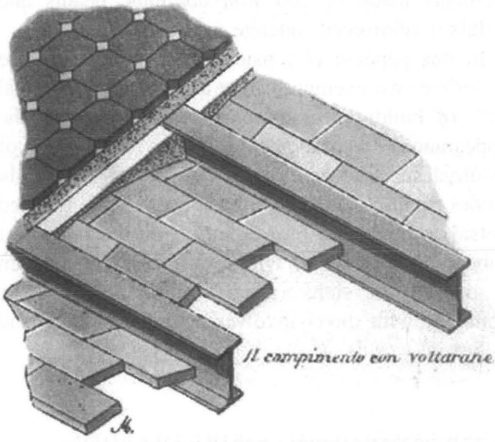


Figure 2
An example of floor made of iron I beams and little vaults in hollow clay blocks (Misuraca, Albertini and Boldi 1900)

Technical and technological solutions more and more assume characters of more complexity and articulation according to evolution of scientific studies and moreover of components which, as said, were born from industrial patents. An example is the case of use of hollow bricks, instead of full bricks, with two, three, four, six holes, or with special shape

with one or more holes: each kiln uses particular shapes in order to obtain more lightness with more cords at same resistance.

Several are the advantages of iron and hollow brick floors: less dimensions (and then less total height of the building), lack of push on confining walls (which may have a minor thickness), more resistance («It has been showed that a floor made of I irons and little brick vaults has a five time resistance more than a floor made in the ordinary way by use of wood and that hollow brick floors are more resistant than full brick ones as first ones results to be more elastic». (Donghi 1905)), more durability and hygienic, less cost (as they were lighter and they required less section of beams and then less use of iron), more soundproofing (due to cavities within bricks). Figure 3.

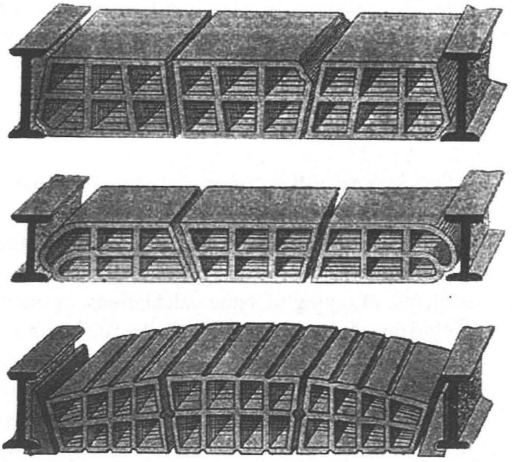


Figure 3
An example of floor made of iron I beams and hollow bricks (Breymann 1895)

a remedial against such inconvenient by producing special impost bricks having a reception cavity for iron beam wing, which then results as covered and proofed against fire.

In parallel to mixed floors in iron and bricks, normally, mixed floors in iron and cement-based materials are used; they are realised with bearing elements made of iron I beams and fillings made in different modality: as an example the so-called «Parisian system», reported by Donghi (Donghi 1905), with rubbles, brick scraps, mortar, chalk and reinforcing irons or iron sheets (longitudinal or transversal) with upper concrete pouring already documented by Cantalupi (Cantalupi 1862). Figure 4, Figure 5.

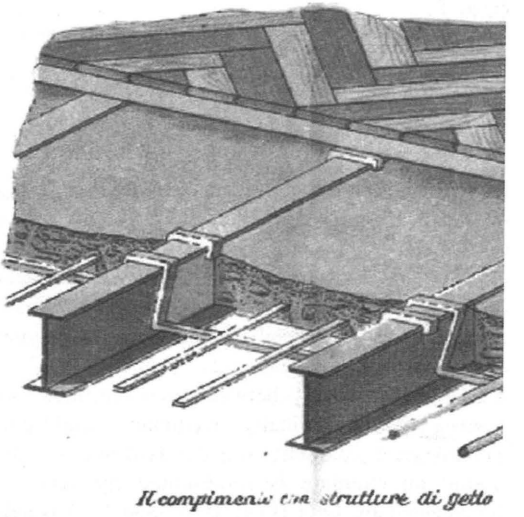


Figure 4
An example of floor made of iron I beams and cement-based materials (Misuraca, Albertini and Boldi 1900)

The experimental and innovative character of technological solution exposes at risk of initial uncertainty: floors made of iron beams an hollow flat bricks, in their first applications don't seem to be safe against fire, as they don't have their lower wing proofed from direct contact with fire. Breymann's Manual (Breymann 1895) and Levi's (Levi 1907) show, with many examples, the way Industry creates

Innovation realised by spreading of iron beams, in a construction process basically kept the same for centuries, doesn't determine a modification of construction, technological, structural and functional conception of residential building complex in its whole (differently by industrial buildings case), as bearing vertical structure mainly remains the same. Architecture, both in new plan-volumetric aspects, in

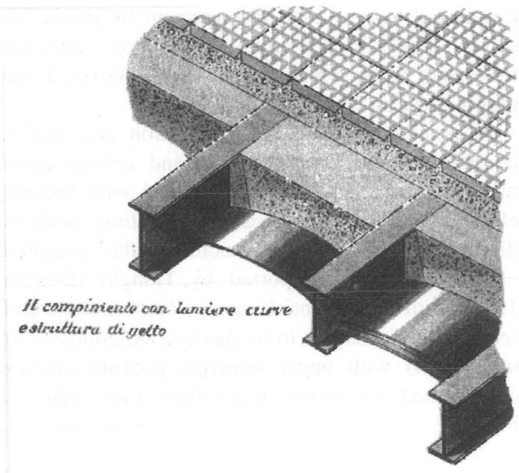


Figure 5
An example of floor made of iron I beams and little iron sheet little vaults (Misuraca, Albertini and Boldi 1900)

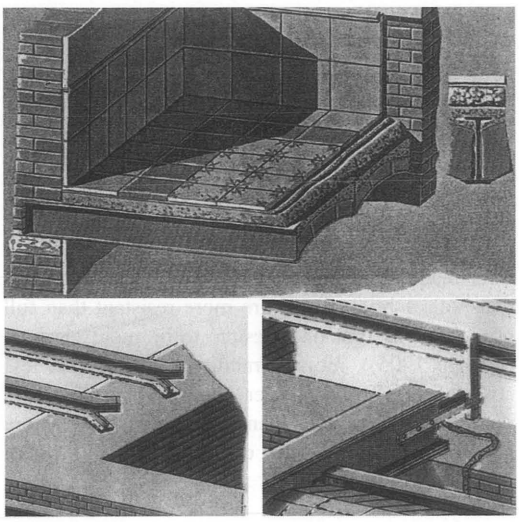


Figure 6
Examples of connections between iron I beam floors and bearing walls, realised by «hard stones» or obtained by use of master key or iron tie (Misuraca, Albertini and Boldi 1900; Levi 1907)

internal distributive characters and in most formal ones, keeps being indifferent to transformation on run, as substitution process has origin in reasons of practical and economical opportunity without being recognised to modern materials and techniques a proper dignity and specificness that means a proper architectural «language».

Even connections between new ceilings and bearing walls basically reproduce traditional technological solutions already used for wooden floors: an example is represented by solutions documented by Levi (Levi 1907) and by Vivarelli (Vivarelli 1913) in which supports of iron I beams upon confining walls are made of «very hard stones» in order to split loads, or the connection I beam-wall obtained by use of master key or iron tie. Figure 6.

And moreover it is sufficient to think to diffuse felt necessity, in residential buildings, to use false ceilings to hide floors and reproduce aesthetic effect of vaulted ceilings. Such false ceilings are made up with complex and articulated technical solutions due to necessity of connection between materials and traditional technologies (as fillers and lathing) and other moderns as the one of «new» floors: an example is given by iron beams and concrete little vaults floor which wooden joints are connected to for the clinging of false ceiling filler proposed by Breymann (Breymann 1895).

Progressive introduction of reinforced concrete structure (happened on the base of intensive experiments, of tuning of static calculations, as much as of evident advantages connected to fire proofing features, of being a unique piece, of possible pre-fabrication, of resistance to earthquake and of different site organisation) doesn't modify in the facts the described situation. In fact, initially, only substitution of iron ceilings with full slab reinforced concrete floors took place: Monier slabs (first application to buildings of studies on reinforced concrete), with reinforcement of round bars crossed and bounded with iron yarn, due to resistance, rapidity and ease of manufacturing are used in substitution of tile little vaults. Consequent numerous patented systems (Coignet, Hennebique, Cottacin, Coularow, Walser-Gerard, to indicate some) only differ according to placement of reinforcement bars and according to this, in order to avoid exclusivity of patents, numerous types «created» and use don site differ following a tradition which prefers practice to theory. Figure 7.

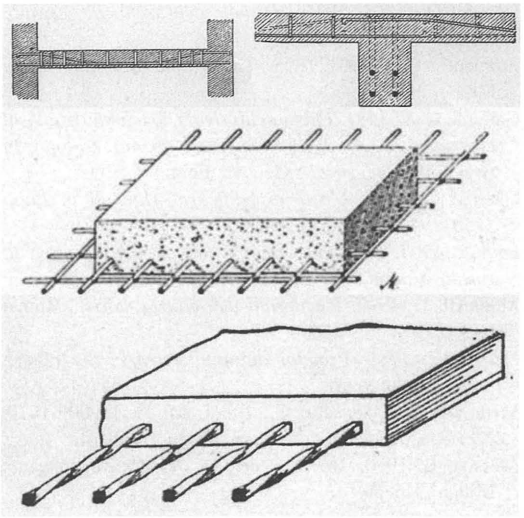


Figure 7
Examples of reinforced concrete floors: Hennebique type, Monier type, Ransome type (Breymann 1895; Levi 1907)

From analyses of different types clearly emerges that need and conditionings of traditional culture keep stay the same: these innovative solutions still provide supports on bearing walls and/or complex and articulated connection systems, as in the case, documented by Formenti (Formenti 1893) of Matrai floor, in which slab reinforcement is made of yarns and steel cables connected to masonries by use of hooks anchored with vertical stakes drowned in masonries themselves. Mentioned conditioning are not only to a technical-technological level but also to an aesthetic-typological one: an example is made by different solutions of reinforced concrete slab floors so-called air-room floors, which have to respond to mentioned aesthetic need of hiding eventual ribs or visible bearing elements by mean of plain false ceilings made of reinforced concrete and/or hollow flat bricks (Frazzi, Corradini systems). It is also this need that determines, after, studies and spreading of numerous kinds of floors made of concrete and artificial blocks.

The truth is that it is the structural and construction building conception that changes in a more or less conscious way for operators: more loads and strength of horizontal slabs, more efficient connections between horizontal and vertical structural elements, less capacity of the masonry structure to undertake light differential assessment, are only some of the new features of building complex.

Further evolution of studies and technological solutions, on one side, and functional needs, on the other, determines spreading of frame structures, which means the use of beams and pillars, in a first time only for substitution of main wall of buildings.

They are first application of Hennebique's patents related to results of study on linear concrete elements, diffused all over Europe due to an advertising campaign and to a network of agents that show the «new» material as a marketing and not experimental product, characterised by precise requirements: lightness, resistance, cheapness, fireproof.

Construction conception is still related to traditional building in masonry: central frame structure is introduced as an independent sub-system, aimed to solve specific static problems, but without considering effects determined on building complex. This, by the way, has got to have an external covering which assures, also according to many building codes of that age, «an ordinary aspect» (Morsch 1930).

Only after long time, use of frame structure affects the whole of the building and advantages are receipted as much as possibility even to a distributive-functional level.

Conclusions

Buildings at beginning of nineteenth century, created and made by use of conjunction between techniques and materials deeply different according to substitution and overlapping process which to apparent and immediately perceiving positive effects puts beside contradictions and potential «aspects of crisis», is subjected to an aging process ascribable to a material and «technological» decay and to a not less important «typological aging» referable to organisation and distribution of internal spaces.

The research, still on run, allows systematisation of a knowledge which constitutes the preparatory phase to analyses of decaying process of such building heritage. Starting from the study of technical-construction features of masonry structures and of transformation when substituting materials and traditional construction elements with modern ones,

next stage is to locate potential lacking point where decay phenomenon can generate under technical, construction, functional, typological and code profile.

This in order to define specific methodologies and guidelines, procedures and operative proposals aimed to maintenance, conservation and requalification for restoration of performance quality of building of beginning of nineteenth century.

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Ornament in Hellenistic architecture: Standardization in construction processes and the birth of the artistic industry. Hypotheses of updating, using CAD/CAM processes

Annalisa di Roma

The main treatises about Classical Architecture and Stereotomy consider the Architectural Orders with their related elements, as a model for stone construction, in which principals of Composition and Construction are given as a result of exact proportional correspondence and numerical relations.

In the Hellenistic period, the relationship between Geometry and the principals of construction became very strong, as new rationalistic ideas of beauty as a product of mathematical relations[1] replaced the aesthetic conception of Art as a product of God's inspiration, codified according to the canons of harmony and rhythm, like Music and Poetry.

Rigour in *geometrical models* is the fundamental characteristic of the main Hellenistic monuments, both in the planning of the Order[2] and in the planning of ornament too.

Geometrical and Construction rules, according to *tectonic* and *stereotomy* principals, become essential, given that the elements of architectural decoration of the temple gained meaning in the use of repetition in series and in the device of mutual combination, which followed the passage from multiplicity to unity. The formal iteration process intrinsic to the Hellenistic aesthetic and to the principals of decoration, characterize the whole building structure. In the trilith building, in fact, each element is submitted to the rule of the series. Each element is conceived of not as unique and unrepeatable, but as a characteristic of reproduction, to emerge as a model for composition and technical principles.

The passage from the unique sculptural model (the original) to the serial, simplified model (the copy)

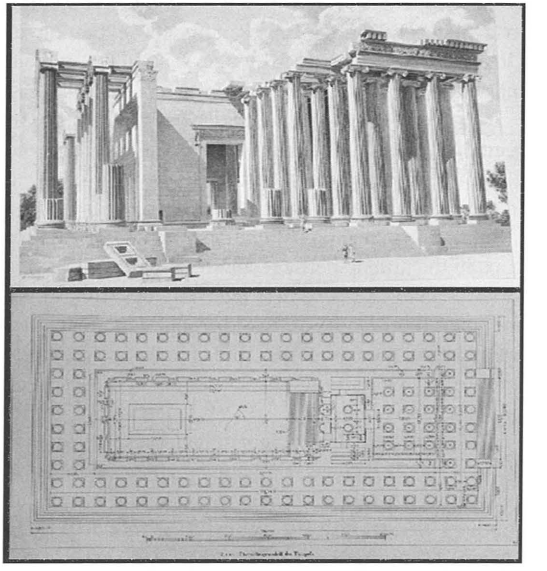


Figure1
Drawing of Temple, archaeological survey made by George Nieman in 1912 for the DAI in Berlin (supplied by the DAI, Deutsche Archaeological Institut, Rome)

takes place through a process of stylised methods that are to be considered fundamental to grand architecture (see the Temple of Apollo in Didyma) and civil architecture (the *stoà* and the Colonnate strips of the Syrian town).

This paper intends to analyse the artistic production of the «special piece» and the methods and proceedings of serial production in order to discuss the birth of the artistic industry.

Hellenism and the birth of the artistic industry

Art collection and copy industry

The enlightened rationalism that characterizes Hellenistic culture determined the organization of scientific and artistic activity through the creation of research centres, museums and libraries and operated according to the principals of the division of labour in the intellectual field.

Artistic production was employed in the creation of complete Art Collections. Princely and private collections already existed but only during this period is the collection systematically organized according to a plan: collections representing the evolution of Greek art, characterized by the search for ancient masterpieces, was begun.

It is very important to notice that this process, regarding the acquisition of classical art, is achieved also through the birth of artisan workshops engaged in the production of copies.

In this way the copyist craftsman compensated for gaps in the artistic heritage and became involved in a kind of rhetoric or exercise that provides, first of all, for an enrichment of the formal repertory and secondarily increases the spread of new technical knowledge in proto-industrial serial production and process.[3]

In the passage from the original artistic object to the series of replicas and copies, it is possible to recognize the beginnings of standardization in production methods: the geometrical model and the Original, numerical model and the Copy.

The principal characteristic of the artistic object, the special unique piece, is that only the author who conceived it masters the geometrical model. The original is followed by replicas[4] made by the same author, or by another one, who reproduces the original geometrical model and becomes adept at reproducing replicas, creating thus new, unique objects. Following this logic, the last steps in the sequence is the creation of copies, realized by hand or by machine, similar to pantographs without any plan. Selecting points from the original, the craftsman develops a kind of mathematical model that becomes the basis of the copy. Mathematical models were often very similar to the originals, the difference between the original and the copy being technical.

When these copies were produced on a large scale for the art trade, this kind of technical difference began to be codified using stylised methods.

Design and building: construction enterprise organization and the architect's role

Works of Classical theory of Architecture were focused on the aesthetic principals of Proportions and Relations between elements of Order, according to the principals of rhythm and harmony, fine refinement and perfect execution, which were the principal topics of such works.

Hellenistic works on architecture speak about mechanics and engineering[5] showing the change in attitudes to a research in architecture and building. The search for new aesthetic reference models ceased and models were taken directly from classical tradition. The aims of Hellenistic theory were the invention of new civil and religious building typologies, conceived to be grand and to give resonance to the expansionist politics of Greece.

Architectural theory was divided into problems of Aesthetics and Practice. Formal decoration became eclectic with a contemporary use of subjects consolidated and codified in the Classical and Ionian periods, and new subjects taken from Asiatic traditions (for example decoration in Didymaion is characterized by the use of actical profiles in mouldings and samic subjects in the decoration). On the technical side, more rationalized processes in stonework took place, based on the specialization of work phases and on the creation of an artisan dimension in serial production.

This kind of specialized organization was based on the use of different workers for the same building and for each carved stone, the aim of skilled work was

speed of execution and a good finish. However, in Greece the reunification of different areas in a single, large enterprise was never realized.

The Temple of Apollo at Didyma is an example of the grand Hellenistic Ionian building in which many different classes of worker were employed for a very long time (the construction started around 334 B.C. and went on slowly for 600 years —it was never finally finished) creating a structure made of 108 columns. Greek workers were used at the beginning and Roman workers at the end. According to H. Lauter (1986) workers assigned to the Didymeion were a sort of stately slave.[6] There were four main categories of worker: the *latomai* assigned to the *quarry phases*, the *leukorgoi* who transported the handmade stone blocks from the quarry to the Temple yard, the *egemon, a* supervisor who directed the activities of the other two classes of worker, and finally the skilled craftsmen, responsible for the *yard phase*. The Latomai quarried stone blocks congruent in dimension to the planned architectonic elements and gave the essential geometrical shape to the stone. The *Leukorgoi* transferred the pre-manufactured blocks to the temple site and then began the process of shaping and refinishing them (*anathyrosis*). The architectural stone element was situated according to the codified position of Order. In the last phase, the skilled craftsmen carved this element following the ornament design made by the architect of the temple, copying a model for capitals;for the column entasys, for the moulding profiles and the architectural decoration they utilized a guide-plane, as well as with strips sculpted on the blocks of the wall of the cellar and the stylobade. These are the blueprints (fig 2) for the temple discovered by Lothar Haselberger in 1979.[7]

The architects Daphnis of Mileto and Paionios of Ephesus designed Didymeon. In the Greek practise of planning the construction phases of the temple, there was an *architekon* and a *hyparchitekton*. The first was essential to the life of the building, he was familiar with the complete architectural plan, directly involved in part of it and directing the work in progress. In the building yard he was responsible for the technical direction of all activities and, completely independently, could plan and approve small interventions in the immediate building area. The *hyparchitekton, on the other hand,* was committed to the direct supervision of each individual block production. In this kind of organization seems to be very clear the strong relationship between design and construction.

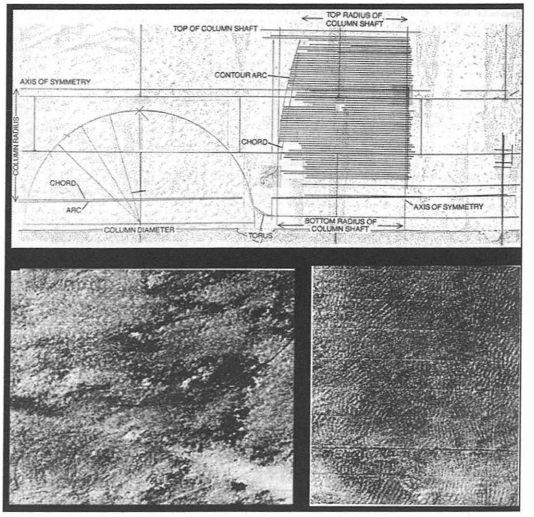


Figure 2
Blueprints for the temple discovered by Lothar Haselberger in 1979 (from Haselberger, 1985)

Morphological development of elements pertaining to the Orders through the process of standardization

In the wake of evolution in building types and large scale production processes, elements pertaining to the classical orders have undergone a series of noticeable changes regarding formal details as well as involving substantial modifications to the morphological characteristics of blocks, both due to the diminishment of the original structural role. These changes effect, above all, elements of moulding and entablature.

What initially might appear as a new form or as an added form to the ornamentation, is, in reality, evidence of how the tectonic quality of building elements have lost their original strength.

With regard to moulding, the most substantial variations can be seen in the *Doric triglyphon*, an eminently tectonic element in which it is possible to witness a noticeable loss of the sense of alternation between *metope and triglyph*. The *metope*, which

originally represented an interruption in the pattern of the wooden beams, increases in size, giving space to the secondary plastic. This expedient was aimed at creating a plastic effect of *chiaroscuro*, eliminating for the most part the structural differences between *metope* and *triglyph*; the represented objects, in this way, have a structural role, upsetting the tectonic sense.

The manipulation of building elements such as entablature (or frontals) reveals not only a clear variation of the structural role but the whole traditional system, based on a clear relationship between single blocks and the organic structure, is called into question. Even blocks used in the cornice reveal a progressive deconstruction of the original monolithic aspect.[8] The cornice becomes an assemblage of movable pieces, attachable and detached.

In this way, compositional processes are born based on the concept of series repetition and to which completely new formal qualities are associated, with new proportional relationships between the various elements.

In general, these morphological and tectonic changes are most evident in the reduction in thickness of the blocks, an aspect that responds directly to the economic obligations imposed by primary materials, and to the increase in production speed and assembly necessary in the construction of civic buildings, for example the *stoà* and the colonnades of commercial Syrian cities.

The Ornament in Architecture

Mouldings and decoration

The analysis of architectural ornament begins with the distinction between *mouldings*, pertaining to the architectural field and *decoration*, pertaining to figurative one. During the archaic age the association between decoration and profile was rigidly controlled,[9] while Hellenistic culture was open to new combinations. Indeed, during the Hellenist period an enrichment of the formal repertory, made up of different styles and traditions, takes place.

Mouldings are serial architectonic elements set in a Greek Order and their sequence and combination generates the language of stone trilythic architecture. According to the archaeological tradition, they are represented by two-dimensional sections, representing combinations of circular arcs filled to create the *listello, cavetto, gola rovescia* and so on.

From an architectural point of view they are parallel-piped stone blocks, characterized by three planar and orthogonal faces and one sculpted surface, extruded to cast a linear or a curved path.

Indeed, each face of the block is precisely refined: the contact side of the block is scored to create the *anathyrosis*. This kind of finishing allows for the perfect assembling of the block and, most importantly, functions as a device to pass from the single block to the organic structure of the building as a whole (from the unique to the multiple).

According to Karl Böttier (10) this kind of morphological envelope corresponds to the Tectonic needs. He says that Tectonic referring to Greek architecture means exact and congruent functions of the members into the Order's system according to their structural role.

In the Doric Order, ornament represents the *stone* evolution of the archaic wood temple and mouldings were scantily decorated. The Ionic tradition allowed for more decorative themes, often inspired by natural subjects or of a textile derivation. Leaves, weavings and meanderings are the most characteristic decorative themes from the Archaic period to Hellenism. Those natural or fictile subjects were processed by geometrical and stylised methods to become repeatable in succession, in the same moulding or the same building and beyond.

Decoration was applied to painted or sculpted moulding profiles.

Standardization in Hellenistic ornament production

Stone architectural element production has always been dominated by a series of rationalized proceedings that are to be intended as a series of operations organized to create a finished product, and methods that are models for specific action.

The first operative stages in ancient stone working, followed standardized procedures and methods in the quarry itself and included quarrying and squaring These two operations were regulated by standardized measures congruent with the architectural element to be realized. The stone blocks

are first worked in the quarry where they are squared. The quarrying of the stone was performed following the precise economic need of limiting off-cuts. The stone blocks were thus quarried according to the required size and type of architectural element to be fashioned. The second operation performed in the quarry was the squaring of the block, a task performed with great care as an ill-squared or imperfect face could compromise successive work phases. The next phase includes the rough-shaping of the block, using *dime* and *huges* and *subbias*, before the successive, final finishing. The process of ornamentation is only partly realized before the block is put into position, or until the process of moulding is begun. (Tav. I)

These initial work phases saw at least two classes of specialized workmen working on the same block and it is probable that different workmen worked at the same task. In such cases, it was essential that the work proceeded according to standardized methods, given that the various sculptors involved worked towards finishing a single block. Mouldings or capitals for example had to reveal the same pattern on different sides.

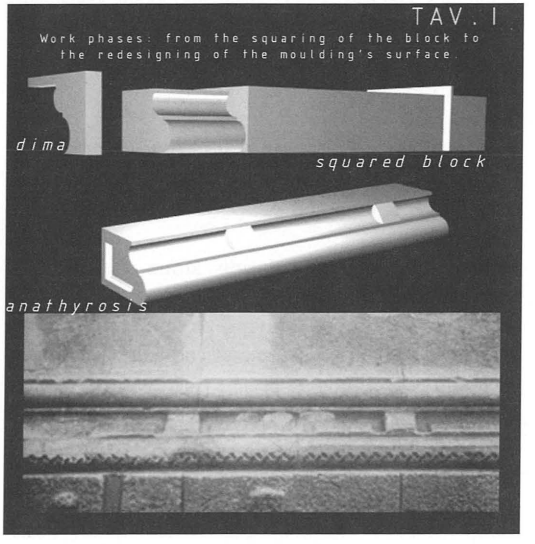


Figure 3
Synoptic plate I, work phases from the squaring of the block to the redesigning of the moulding's surfaces. Drawing by the author (September 2002)

At Didyma, general information about the shape of the moulding sections, the size of the *enthasis* of columns etc., is still visible on the cell walls and on the stylobate blocks because, as this Temple was never finished, such graffiti, which represents the Greek working methods, was never smoothed off or cancelled.

The mouldings were sculpted with stylised decorative sketches, which functioned as a guide for the artisans who decorated the stone. Following this method of directing work by architectural sculptors, the final surface is sculpted before them. The sculptors were required, above all, to produce a faithful copy of the original. Finishing of blocks with flat surfaces was performed once the block had been positioned in the wall. The sculpting of contact surfaces (anthyrosis) had to be performed with great care as they were the principal elements of formal juncture between surfaces that had to be perfectly flat and those which continued the decoration. Evidently, the façade had to be sculpted once all the blocks were in position.

The development of the idea and its development before and during the work phases, constitute the technique of stone working.

Decorative patterns: planar curve to surface (TAV.II, III)

Decoration could be developed following a process of either *direct* or *indirect design*.

In the first case the artistic component of the sculptor, who develops his own design directly on the stone, prevails. This methodology is contrary to the principles of standardization, and its the final product is a «special piece», that is difficult to produce and reproduce in faithful copies for the team of stone masons.

Indirect design implies characteristics of repetition, and the decorative pattern corresponds to precise geometrical rules, which prevail over the purely figurative components.

The method of direct design in Hellenistic architecture was predominantly used in the production of «special pieces» to be inserted into buildings as representative of a certain monumental spirit. The indirect method was more commonly used in the serial production.

Moulding's surfaces are always being developable in planar surfaces: this means that it is possible to study the decorative patterns in their planar configuration, and to project the planar curve to surfaces. In this way starting from the original configuration of the decoration is possible to achieve different kinds of 3D patterns, according to the development surfaces, both linear and/or generated by revolution, on which it had been projected.

In this light the Decoration design could be divided in two main phases:

— The first regard definition of two-dimensional pattern.
— The second pertain to the study of the three-dimensional moulding's surfaces and their related planar development.

The two-dimensional decoration is proportioned to the planar envelop of moulding's surface and then projected on the three-dimensional surface. This method is based on the geometrical principle of congruence between surfaces and planar curve developed.

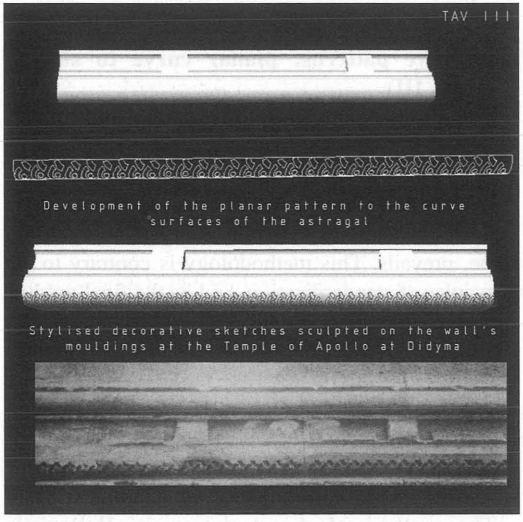


Figure 4
Synoptic plate II, Apollo Temple at Didyma: development of the planar pattern to the curved surfaces of the astragal, and stylised decorative sketches sculptured on the moulding's surfaces. Drawing by the author (September 2002)

In the ancient methods this theory was applied in the determination of stylised guide line sculpted in the first work of the row block.

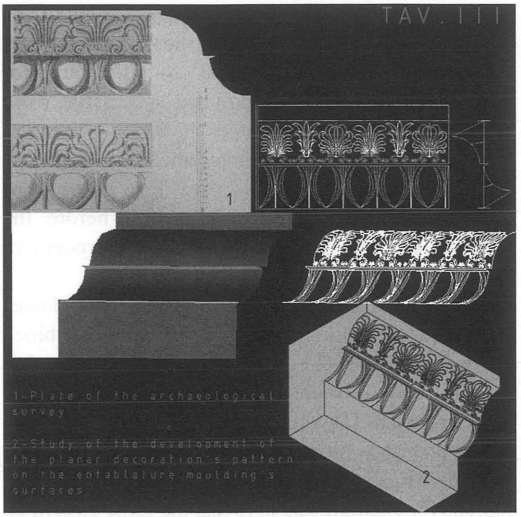


Figure 5
Synoptic plate III Apollo Temple at Didyma: development of the planar decoration pattern on the entablature moulding's surfaces. Drawing by the author (September 2002)

Standardization in cad-cam processing.

Cad/cam methods and processes

The hypothesis of updating stone architectural ornament design and production processes is based on the possibility of applying modern stone cutting technologies through the use of cad-cam. The aim of such a research hypothesis is the development of contemporary architectural forms to be used mainly in restoration sites.

Electronic Design replicas, referred to ancient Orders and Ornaments, allowed us to comprehend the complexity of classical geometrical models and technical knowledge in sketching and finishing surfaces.

Starting from the study of the single special element, the reflection led to the methods that are to

be consider valid for replicas and copies' serial production.[11]

On the basis of the archaeological survey's data, the Cad design allowed us to reproduce the original geometric model and to make a virtual three-dimensional replica, that could be considered likely identical to the original.

Cam processing concerns the planning of work-phases in making replicas.

The first step is to import cad project files (dwg, iges and so on) and then to choose the number and the kind of processes, the number and the kind of tools.

Work cycles are divided into two main categories, rough-shaping and finishing. These two phases of work in progress correspond to a growing approach to the form, from the parallelpiped block to the final ornamental element.

The second step is the tools' choice, the number and kind of which depend on row-block dimension, final element morphology and the kind of sketching and surface finishing. In the tools repertory we distinguished two main categories: those which use their form to reproduce predisposed form and those with a cylindrical or spherical form. The first kind of tool is generally used to make contours and incisions, the second type in rough shaping and finishing. The variables to be decided on in choosing tools include rotation speed and progress speed, depending on the characteristics of the stone and the shape to be achieved.

The last steps in a CAM project is the generation of CN files[12] made by a cam software. This file contains all the information about labour, finishing and tools changes.

Sketched and finished surfaces in the ancient age and in Cad-Cam production

The tools choice and the techniques of rough-shaping and finishing are important for any research project that intends to recover the expressive nature of stone, since certain plastic outcomes of the period are to be

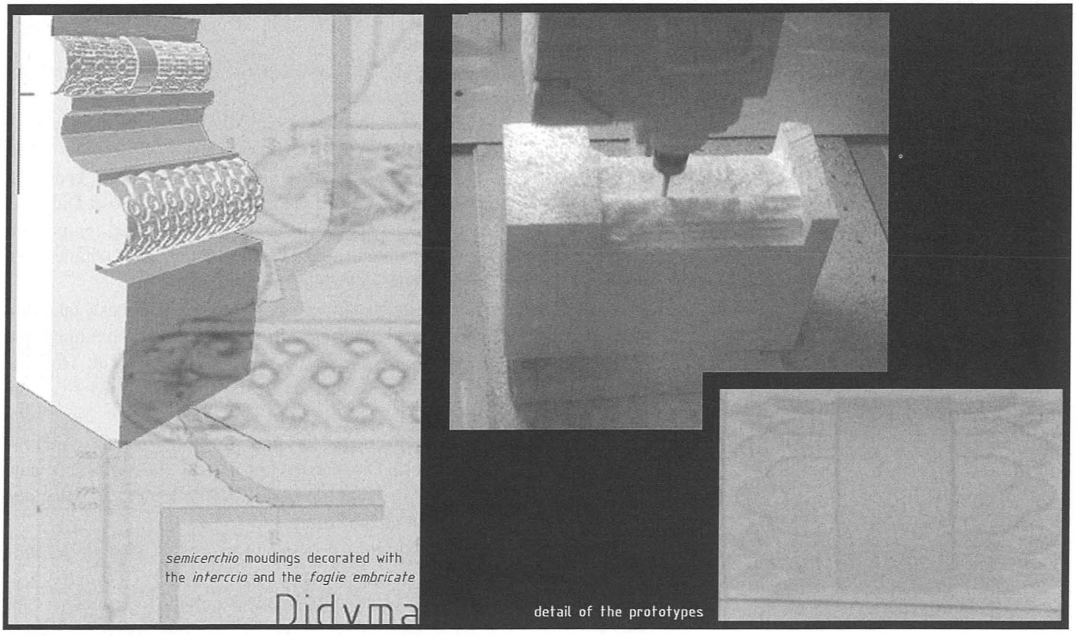


Figure 6
Synoptic plate IV Apollo Temple at Didyma: the 3D virtual model of the naikos wall base's moulding, and CNC Work phases for the prototype's realization (Laboratorio Cad-cam, Dipartimento ICAR, Scienze dell'Ingegneria Civile e dell'Architettura, Politecnico di Bari, June 2002)

evaluated as the result of the tools which were used for the percussion.

The study of the artisan ornamental techniques used in Hellenistic building sites permits a comparison of the similarities and differences between a manual production system and a mechanical system using numerical controlled machines.

In ancient building sites the constructions of finished elements necessitated a series of work phases (often performed by different specialists) analogous with mechanized systems in which the number of jobs to do depended on the nature of the object to construct and on the type of ornament.

A decorated surface would be subject to at least three work phases, which would increase in relation to the morphological characteristics and to the number and type of tools necessary to the stone-cutting. In the ancient period the production of different blocks was often the responsibility of various workers and the result was a slight difference between the pieces. The production of a series of elements entirely produced with mechanical processes, on the contrary, guarantees absolute similarity.[14]

In the ancient period the first work phase after the squaring of the block was the redesigning of the orthogonal surface of the moulding. The pattern was accomplished using *dime* and boring tools. The *dime* were generally made in wood and appear as the negative of the mouldings, they permitted the control of the required shape during the sculpting process. The circulation of templates and pattern cards throughout the building sites was associated with the mobility of artisans and allowed for the rapid execution of similar elements. Only in the final surface finishing phase were abrasive tools used.

The mechanized processes employed by computerized numerically controlled machines use mills and rotating drums which need materials with different characteristics to those required by scraping off tools. Certain processes (including «bush hammering», which is typical of the surfaces between the blocks and the drums) do not appear to be reproducible with off-cut techniques. Thus it is necessary to establish *a* priori both the type of tools necessary to create the desired effect and the right type of operation (wholly mechanical, partially manual etc.). This problem is more complex in the study of decorative pieces, in which the finished product reveals both intaglio and, sometimes, fretwork.[13]

Notes

1. The philosopher Platone in the *Res Publica* expresses the conception of beauty as a strong relationship between geometrical shapes and mathematical proportion.
2. Doric Order was exactly ruled in the VI B.C.c. and only few changes in decoration and proportion appear during the following centuries. The architects of the Asia Minor codified ionical Order later in IV B.C. c.
3. «Accanto alle botteghe dei ceramisti, che in parte lavorano già con sistemi industriali, comincia la produzioni su vasta scala di copie dei capolavori della scultura. Senza dubbio le stesse botteghe e le stesse persone producevano anche opere originali ma è naturale che gli scultori, esercitando quel mestiere di copisti, si lasciassero facilmente sedurre dal puro virtuosismo stilistico». (Hauser,1986)
4. Kugler (1972) gives a precisely distinction between original object and copies according with aesthetics' principles. The formal class is expressed «da oggetti primi o da cose dotate di grande potenza generativa, quali ad esempio il Partendone [. . .]. Anche se parte del loro splendore è andato perduto col tempo, la loro qualità di oggetti primi resta indiscutibile».
5. Vitruvio dedicates the Xth book of the *Ten book on Architecture*, to the construction of machine for the construction.
6. Building's enterprises were generally managed by private organization.
7. Lothar Haselberger (1985) discovered in October '79 many etched line on some of walls of the Temple. Then he realized that those strips should have been the construction plans for the temple of Apollo at Didyma.
8. Trevor Hodge (1960) makes an interesting comparison between the cornice's blocks of the main temple from the Archaic to Hellenistic age.
9. According to Giorgio Rocco (1994), Greeks inherited from Egyptian Architecture the two main moulding: the *cavetto* or *gola egizia* and the *semicerchio*. Hellenic culture taken this two forms and developed five new form. The *semicerchio* was used in his linear and original form and became the *toro* for the columns' bases. The *becco di civitta* and the *gola rovescia* were typically used in the Doric Order and *gola rovescia* and the *ovoli* in Ionical Order.
10. Karl Bötticher, neoclassic architect and architecture's theorist.
11. Prof. D'Amato (2002) speaks about the replica of the 9A Doric Capital of the Temple of Apollo Epicurio at Bassai. He makes a comparison between an artistic replica and an architectural one.
12. A CN file is written in an ISO-normalized format and adapted to characteristic of the Numeric Controller

Machine by the CAM-software. The file elaborated by the author was processes by the cam software of the Easy 11 CNC machining centre of the Laboratorio Cad-cam at the Politecnico di Bari for the realization of a first moulding prototype with the *imbricate leaves*, presented during the Study Seminar «ARCHITETTURA E STEREOTOMIA: TRADIZIONE E INNOVAZIONE. Giornata di studi sull'Architettura in Pietra da Taglio», 3–4 June 2002).

13. The paper summarises some aspects of the on-going Doctorate dissertation the author is carrying out at the Politecnico di Bari, and titled *La decorazione Architettonica ellenistica: dal pezzo singolo artigianale alla produzione in serie*. Tutor: Prof. Claudio D'Amato Guerrieri, Politecnico di Bari, PhD Course in Progettazione Architettonica per i Paesi del Mediterraneo, ciclo XVI.

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An endeavour to identify Roman bridges built in former *Hispania*

Manuel Durán Fuentes

Over the course of history, bridges have enjoyed wide social acclaim as proven by the numerous references to them in popular tradition and in historical documents. This has not been reflected in the field of surveys however, where the number of books devoted to the subject is quite low in comparison with that of those centred on architectural works. The first specific study of bridges was written in 1716 by Henri Gautier. The fact is that historians have shown little interest in ancient public works and engineers have not paid too much attention to them either.

Following the establishment of new policies of preservation and appraisal developed in Europe in the second half of the twentieth century, when the notion of heritage transcends architectural monuments, this tendency would change and the historical and heritage value of many technical constructions (former industrial installations and historical public works in general) began to be acknowledged as new categories of cultural heritage were defined. Within this new context, in recent decades a number of studies have appeared on ancient bridges which, in general terms, describe the works in question and provide historical documents yet without analysing in any great depth the stonework, an essential factor in the investigation of their constructional history, above all in the cases of the oldest bridges, on which scant documentation is available.

Our study will focus precisely on this feature, and will attempt to furnish a systematic analysis of the formal and constructional characteristics of Roman bridges in *Hispania*, applying a method of work that has enabled us to reach a series of conclusions which will prove vital in the identification.

Methodology

Over the last few years a certain methodology has been developed to further the identification of the Roman bridges in *Hispania*, based on the analysis of the stonework of surviving bridges (Durán 1996; Durán 2001). Initially the idea was to gather the maximum amount of information published on the bridges in question, all of them of unquestionable Roman origin, and to obtain as much data as possible by means of precise topographical upliftings of them all. Varying historical and territorial determinants were taken into account, as was their transformation over the course of time, while other geo-technical, structural and hydraulic factors were also analysed. The resulting data has enabled us to systematise these works, and obtain a set of constructional and formal features that will prove extremely useful in ensuring accurate identification.

It is difficult to date these bridges with precision due to their formal and constructional likeness over various centuries, which has led us to restrict our object exclusively to identifying them. This limitation will no doubt be overcome in future thanks to the undertaking of new historical, archaeological and constructional studies in the sphere of the former Roman Empire.

Analysis of Hispanic Roman Bridges

Bridge building throughout the Roman Empire was carried out by technically skilled specialised workers in the military, whose work was no doubt subject to precise rules. The stonework, a paradigm of fine construction, was executed in a solid stable fashion to ensure its eternity, as described by Caius Iulius Lacer, the architect from Alcántara who erected his work for it to last «forever, over the centuries of the world».

Standardising the intrinsic features of such constructional rigour will enable us to identify the possible Roman origin of ancient bridges. Yet scholars have not always proceeded in this way, and have occasionally identified bridges as Roman when these presented stone vaults of an indefinite date, or merely influenced by the popular term used in reference to them. In our opinion the adjective «Roman» should not be applied indiscriminately to any bridge that happens to exist where a former Roman bridge once stood, but exclusively to those bridges that have preserved their original stonework almost entirely, or else those that, while only preserving a part of this, are still distinguishable as Roman despite subsequent reconstructions. The Sommieres bridge in the French region of Provence for instance, can be considered Roman in spite of its successive reconstructions, for it preserves the shape and many of the specific features of Roman works. On the contrary, Ponte Vella in Ourense cannot be regarded Roman despite having preserved a part of its original work, because Mediaeval and modern reconstructions have completely altered its primeval



Figure 1
Bridge of Sommières

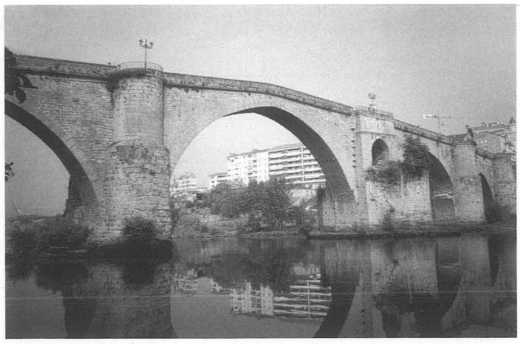


Figure 2
Bridge of Ourense

form. In cases that do not fall neatly into either category, we have opted for the expression «bridge in the Roman tradition» describing works which, in addition to possessing certain historical conditions, present other constructional features that enable us to presume the previous existence of a Roman bridge in the same spot.

The task of identification proves easier in the case of ashlar masonry, as the scabble, the bond and the painstaking execution are the first clearly recognisable signs. In the case of ashlar (*opus vittatum*), schistose, brick (*opus latericiae*) or a combination of these materials, the difficulty increases, for such works are barely distinguishable from others made at a later date. No bridge made of masonry or of flagstones has been identified in former *Hispania*, and only one built of bricks has been officially recognised. A schistose bridge quoted as Roman is the one on the outskirts of former *Asturica Augusta* (Astorga), on the French road to Santiago. At present somewhat covered by earth, it presents segmented arches measuring 3.60 m wide and its roadway has a slight double slope. Having analysed the work in some depth, one reaches the conclusion that none of its features allow it to be identified as Roman, an assumption reinforced by the fact that it stands outside the route uniting Astorga and León.

Identifying brick bridges is not an easy task either, as this material has remained practically unaltered over many centuries. Only the size, constructional layout and comparison of such works with other Roman examples allow positive identification. The Mérida sewer (Alcantarilla de Mérida), the only

work classified as Roman, was built on the former road between *Emerita Augusta* and *Bracara Augusta*, according to a plan drawn up by the master builder Fernando Rodríguez in 1796 (González Tascón 2002, 143). The size of brick used in this bridge was 29.6 × 44.4 × 5.5 cm, laid out in radial stretcher and header courses, exactly the same as the Roman bridge in Saint Albans, England (Harney 1990, 45). The stonework in another example, the Roman bridge in Carmona, however, presents no specific feature betraying such an origin, despite standing in the place where a wider bridge had existed previously, according to remains preserved on both abutments and a layout resembling arcading. Yet the Roman bridge over the river Odiel, in the vicinity of Aracena, standing on the *Urion-Arucci* road (Ruiz Acevedo 1998, 84–85) did perhaps preserve a Roman arch, the one with the smaller span, presenting the same constructional characteristics as the Alcantarilla de Mérida.

Of the thirty-two bridges in *Hispania* (Spain and Portugal) examined in this study, only one preserves very few remains (Aljucén bridge in Cáceres), while six others preserve quite a significant proportion of original stonework and have suffered a number of reconstructions (Ponte Vella, Ponte Cigarrosa, Ponte Navea and Ponte de Baños de Molgas in Ourense, Ponte Romana in Lugo and Bridge of the Devil in Martorell). Two are of dubious Roman origin yet have traditionally been regarded as Roman (Villa del Río and Los Pedroches bridges in Cordova), and the remaining twenty-three preserve much of their original stonework (Durán 1996, 167–178). The studies carried out have allowed us to determine nine characteristics or constructional features taken as the basis of the identification process.

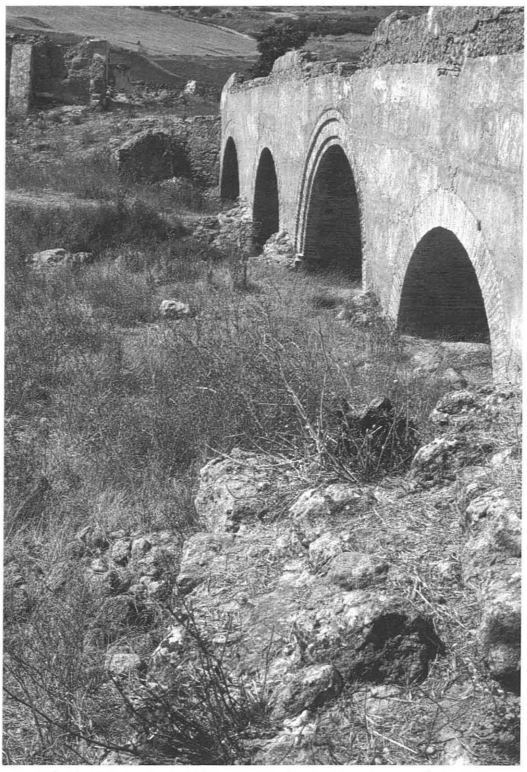


Figure 4
Bridge of Carmona



Figure 3
Mérida sewer

Formal and Constructional Singularities of Hispanic Bridges

The uniformity of Roman construction in time and space is quite obvious in bridges, as the singularities observed in those built in *Hispania* appear in other works built in other regions of the empire, a fact that enables us to suggest, having defined their peculiarities, that all works that present them, totally or partially, are quite likely to be of Roman origin. None of these features, widely present in Roman works, proves this fact in itself, and must be accompanied by further evidence of a historical or

archaeological nature, for many such traits have been used in bridges built at later dates.

Bridge Width

One of the most interesting features of these works is their width. Most of the bridges built in *Hispania* and in other parts of the Roman Empire are over five metres wide, a significant dimension compared with bridges built later, especially in the Middle Ages, which were seldom so wide. Perhaps this was because Roman builders preferred not to reduce the breadth of the roads (usually six or seven metres wide) on their course over the bridges.

Our study has centred on 146 different widths, many of them measured for this purpose and the others taken from Galliazo's survey (Galliazo 1996). The results obtained show that only 18.5% of the bridges measured less than five metres wide, in other words, 81.5% exceeded this value, while only 5% of bridges had a width of less than four metres. As an example, we present the widths of bridges in Roman *Gallaecia* (Galicia and northern Portugal):

- Between 4.50 and 5.00 m – A Pontóriga bridge (4.50 m), Sao Lourenço sewer and Ponte Freixo (4.60 m)
- Between 5.00 and 6.00 m – Ponte de Lugo (5.00 m), Ponte Pedriña (5.74 m), Ponte San Miguel (5.50 m) and Ponte da Ribeira o Forno (5.50 m)
- Between 6.00 and 6.50 m – Ponte de Pedra (6.00 m), Ponte de Chaves (6.10 m), Ponte Cigarrosa and Ponte Vella de Ourense (6.15 m), Ponte Bibei and Ponte Navea (6.30 m)
- Over 6.50 m – Ponte de Lima (7.10 m), Ponte do Arquinho (7.30 m)

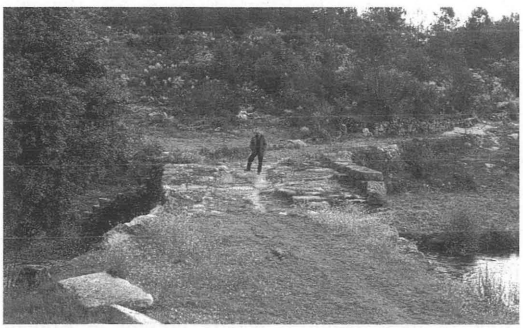


Figure 5
Ponte do Arquinho

The Horizontal or Slightly Inclined Grade Line

The platforms in 75% of the bridges studied have horizontal grade lines, while the other 25% present a slight inclination with slopes of roughly 3%.

If we extend this analysis to bridges in other regions we notice that most have similar characteristics, although those with horizontal grade lines are dominant. Pont Julien, in the French department of Vaucluse, presents the greatest inclination, yet even in this case the slopes are no higher than 9%.

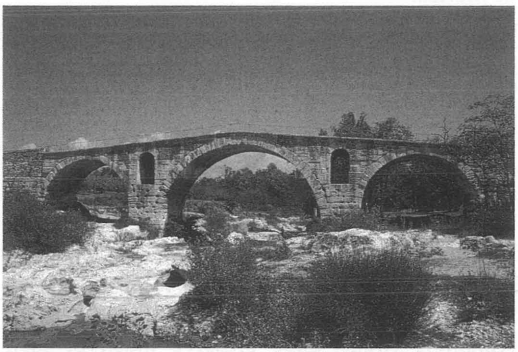


Figure 6
Pont Julien

Rustic Work

Rustic work appears in all the bridges in *Hispania*, and in most of those preserved in other parts of the former Roman Empire. The taste for this form of scabble was a Greek legacy that can be traced back to many military constructions from the Hellenistic period onwards, with aprons made of rustic work (Adam 1982). The reasons explaining its appearance could be both economical, as rustic work avoided carving the totality of exposed face, and practical, designed to protect the edges of the ashlars during their transport and laying up. Subsequent use in

Roman times obeyed aesthetic motives, for when the rustic work was placed in the lower areas of constructions it granted them a sense of robustness (Lugli 1957, vol. 1: 208), as we see in the bridge at Alconetar in Cáceres and in the Bridge/Aqueduct of the Devil in Tarragona.

The most frequent form of rustic work in the masonry of bridges in *Hispania* is rough-hewn exposed face, occasionally with chamfered edges and in most cases with bands dressed with chisels or fine gradines on one or several edges, forming *anathyrosis* (Lugli 1957, vol. 1: 207).

This feature is quite common in Roman constructions yet its mere presence in ancient bridges does not guarantee this origin, as it has been employed over the course of time and has even been copied in reconstructions dating from later periods, thus producing confusion. Rustic work practically identical to the original stonework was carried out by Portuguese stonemasons in the reconstruction of two arches of the Segura bridge in 1571 for instance, such a fine imitation that it is barely distinguishable (Durán 1996, 175).

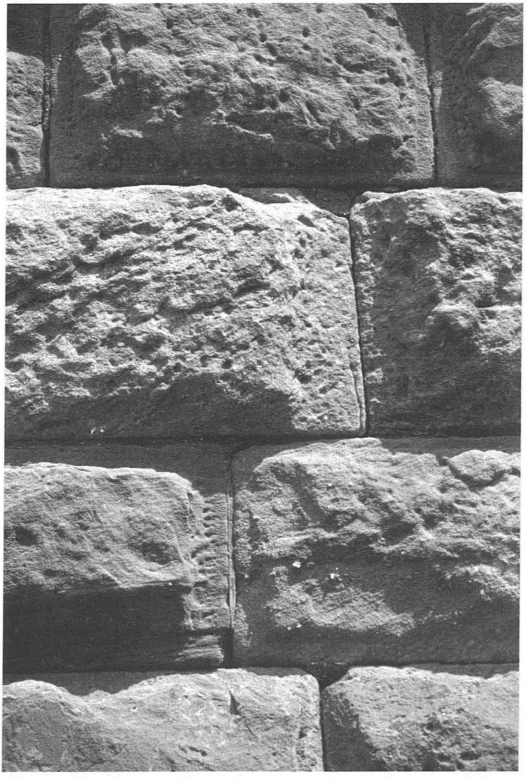


Figure 7
Bridge of the Devil in Martorell

Alternate Stretcher and Header Courses

The alternation of masonry units in stretchers and headers in the same course, or the presence of alternate courses of units in stretchers and headers are bonds that the Romans also copied from Greek construction, where they originally appeared when structures built with logs of wood alternately placed crosswise to grant them stability were subsequently reproduced in stonework. Of the two dispositions, the latter (alternate courses of stretchers and headers) is the most frequent in Roman construction, further proving its systematic nature, well suited to the Roman concepts of planning, efficiency and speedy execution (Adam 1996, 119).

Bonds of alternate courses of stretchers and headers appeared in a number of ancient works such as the Servian Wall in Rome, built between 378 and 352 BC, the walls of Falerii Novi, built in 240 BC and the viaduct of Ponte Picchiao in via Flaminia, built in 220 BC (Ballance 1951, 88). Defined by Lugli as a «Roman system» (Lugli 1957, 175) due to the frequent appearance of *opus cuadratum* in works, it was also employed in a fair number of bridges. Despite having been considered a feature



Figure 8
Ponte Freixo

characterising construction before the age of Augustus, its presence in works of an obviously later date invalidates this opinion (Ballance 1951, 95). This bond is usually found in the lower parts of abutments and piers, designed to connect the stonework of these areas subject to greater thrusts and movements than the rest. In this position we find it in Ponte Freixo in Ourense, where a uniform unit of masonry was employed, measuring 1 × 1 × 3 feet placed in alternate courses of stretchers and headers. In fact it can be traced in 67% of the thirty-two bridges in *Hispania* we have been analysing, usually beneath the springing lines of the vaults in the inner parts of piers and abutments and on the channelling walls.

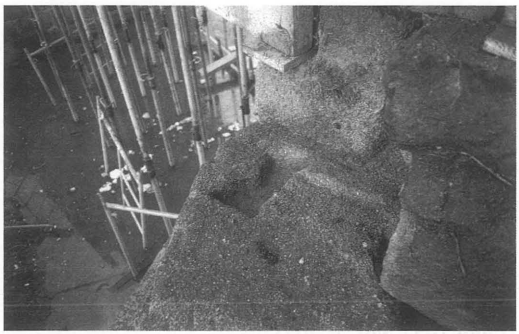


Figure 10
Ponte Freixo

Ashlars with Holes in Dovetail Shape

Roman construction adopted this way of connecting units of masonry by means of leaden cramps or dowels, reproducing joinery. Other more simple forms of linkage were also employed (Ginouvès and Martín 1985, vol. 1: 28), some of them until recently, such as the U-shaped metal cramps identified in Ponte de Pedra, Portugal. This sort of cramp is easy to make by bending the two ends of a reinforcing bar, and equally easy to put in place, as it fits neatly into the two cavities that are then filled by tapping lead to subject it.

As for the dovetail mark, we must say we find it an extremely interesting feature that does not appear in works from later periods. Some authors hold the opinion that this way of connecting stonework died out during the first century AD (Adam 1996, 57), at the height of the Roman era. In our view this was not the case in the construction of Hispanic bridges, for this trait appears in later works such as Ponte Freixo.



Figure 9
Ponte de Pedra

This sort of linkage was placed in those areas of the work subject to greatest external actions, areas susceptible of registering the most important movements, usually the lower spans of abutments and piers, and the paving of the foundation. We have only come across this form of cramp, joining voussoirs, in one case outside of the region of *Hispania*, to be precise in the Chemtou bridge in Tunisia.

Few are the cramps that have survived, whether made of metal (usually stemming from the Middle Ages) or of hard wood such as ash, holm oak or olive. Two were sent by the engineer Alejandro Millán to the Real Academia de Historia in 1859, discovered during the works of restoration of the Alcántara bridge in Cáceres (Blanco 1977, 68), and others were found, reduced to ashes, at Ponte Freixo during the works of consolidation carried out between 1989 and 1990 (Alvarado, Durán and Nárdiz 1989, 69). The scarcity of cramps was taken by G. Boni as the basis of his assumption that the double dovetail did not obey any constructional purpose but was merely reminiscent of the double-bladed axe, an ancient religious symbol widespread throughout the Mediterranean basin (Lugli 1957, 237).

The double dovetail may be difficult to discern in some works, for it is usually placed in the inner part of the stonework and can only be detected if the work is

incomplete or the units of masonry are removed from their original positions. The existence of the typical extraction holes and, if visible, the paving of the foundation also enable us to identify this sort of linkage.

The double dovetail appears in five of the thirty-two Roman bridges in *Hispania*, namely, in the cutwaters of Ponte Freixo, in the channelling walls and the right abutment of Ponte Navea and in the paving of the foundation of the piers in Ponte Cigarrosa and the Segura and Villa del Río bridges. More recently we have also come across it in the foundation and the supporting walls in the Pertusa bridge in Huesca, an example not included among the thirty-two we have focused on.

Uniformity in the Thickness of Vaults

This constructional feature must be clarified, as the uniformity we are broaching should not be understood in absolute terms. Given that practically no bridge has a constant vault thickness throughout its directrix, we have decided to consider uniform only the threads whose variations in height do not exceed 10%. The thickness studied is that of the rib, the only thickness clearly visible in most bridges, as that of the inner areas is only seldom perceptible.

The degree of thickness is more noticeable comparing the vaults of Roman bridges with those on Mediaeval examples, for the latter present voussoirs of more irregular sizes. Some Roman works occasionally evince a lack of uniformity, but this is generally confined to a gradual variation of the height of the voussoirs, from the keystone to the supports, or else to the existence of voussoirs of exceptional size in the springing lines, in the haunches or in the very keystones.

To the relative uniformity of the exterior threads present in 95% of the Roman bridges we have studied, we must add the fact that the works that have enabled us to observe the complete extrados of a vault (Ponte Freixo, Ponte do Arquinho, Alconetar bridge, Ponte de Lima, Ponte San Miguel, Ponte Ribeira do Forno and the aforementioned Pertusa bridge) thickness is constant throughout the width. This is probably true in most Roman bridges, save in exceptional cases such as the ribbed vaults of the Augustus bridge in Narni, Italy, and the vault made of cement and stone rings in the San Martín bridge in Aosta. In Mediaeval bridges however, it is quite frequent to find arrises or ribs that are thicker than the central areas.

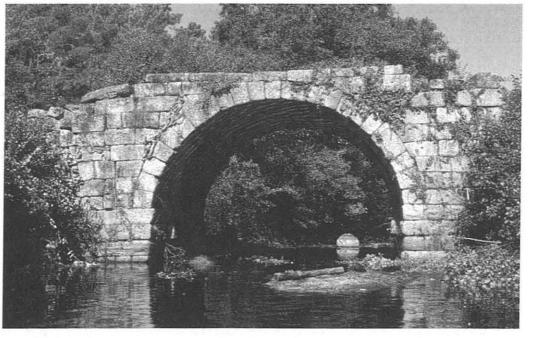


Figure 11
Ponte do Arquinho



Figure 12
Bridge of Merida

Careful Execution of the Bond and Joints of Masonry Units

This feature is also held in higher esteem as opposed to the neglect evident in Mediaeval stonework, as the bonding and quality of the scabble in Roman masonry stands out compared with stonework of later periods. In our opinion, the refinement of the joints and the precise fitting of the ashlars distinguish Roman works and are useful tools in the task of identification.

Manipulation Holes in Masonry

In this section we shall study the holes for hoisting the units of masonry with gripping-tools, and those made on the upper or lower edges of the ashlars to facilitate their positioning with levers.

The small holes appearing more or less in the centre of the ashlars and voussoirs were made to hold the teeth of the metallic gripping-tools (*ferrei forfices*) used in hoisting pieces (Adam 1996, 52). They are frequent in Roman constructions and, of course, in numerous bridges, and their most common shapes are triangular, circular and rectangular. Due to the fact that these holes was not exclusive to this period —the use of gripping-tools similar to *ferrei forfices* is still a widespread practice today— their presence in ancient bridges does not necessarily prove a Roman origin. In spite of this, and given that they appear in 67% of the bridges we have been analysing, we consider them sufficiently meaningful to deserve inclusion in this set of features.

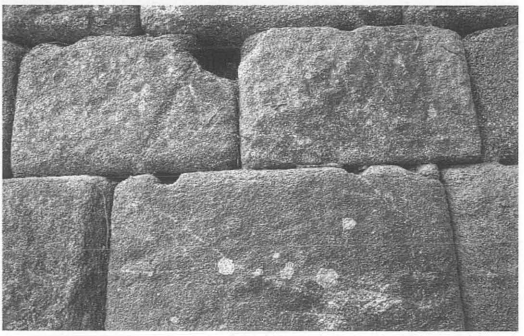


Figure 13
Ponte Freixo

The flattening practiced on the edges of the units of masonry to facilitate their placing in position with levers can be observed in a number of bridges in *Hispania*, such as Ponte Freixo and Ponte Bibel, yet never in later works. This characteristic is typical of Roman constructions and its presence in ancient works can be taken as sufficient evidence of Roman origin.

Dimensions in Roman Units of Longitude

The results of the transformation of the most significant dimensions of an ancient bridge into Roman units must be regarded with some reserve, especially if it is employed as the sole procedure to justify their Roman origin. The first problem appears when it is impossible to obtain accurate knowledge of the original dimensions. This is the case when the origin of the measurements is unclear, as for instance in constructions with rustic work on the joints or on the external face of the stonework (the difference between these two measurements may be of up to fifteen or twenty centimetres). It also occurs when it is likely that the measurements have suffered modifications due to a variety of reasons, as a result of which the bridge will be affected throughout its practical existence (avenues, excess loads, earthquakes, movements, etc.).

The study of dimensions is usually undertaken to discover the modular design of each work and the geometric relations between its various parts, as well as to translate the most significant dimensions into units of measure of the Roman age, generally expressed in feet. Sometimes the results are slightly forced, particularly when the idea behind the use of abundant arithmetical calculations of various multiples and sub-multiples of feet, and even fractions, is to find measurements in Roman units that adjust to the most significant dimensions of the bridge.

This dimensional analysis may prove interesting if and when it is not the only means used to identify a work, but merely a complementary test. This is particularly important if it is carried out with excessive yet useless rigour, employing average metrological values expressed in centimetres, applied either to the search for relations between different parts of a bridge —the golden section of between the

spans of the Alcántara bridge and Ponte Freixo has been discovered— or to the adjustment in feet of the most outstanding dimensions.

Finally, we would like to point out the striking fact that many of the dimensions of Hispanic correspond approximately to whole numbers of feet, and that certain values (10.40 m, 6.00 m, 4.60 m, 3.60 m, etc.) are often repeated.

The Identification of Roman Bridges

In order to further the probability of successful processes of identification the stonework must present as wide a set as possible of the features expounded. Even so, there will be cases in which it will be difficult to reach a definitive conclusion, and the only option will be to wait for new knowledge and research to provide a solution.

We have been studying bridges in former *Hispania* for a number of years now, obtaining a variety of results, some of which we shall set out here. One of the most interesting results is that of the Villa del Río and Los Pedroches bridges in Cordova, constructed on the route of the so-called Via Augusta between *Castulo* and *Corduba*, and traditionally regarded as Roman. However, certain features of the surviving stonework made us doubt this origin (Durán 1996, 177–178). The Roman nature of the bridge at Villa del Río seems justified by the presence of rustic work, by the possibly original symmetric disposition (it once had a fifth arch that has not been preserved), by the existence of dovetail holes in the paving of the foundation and by the typological resemblance to the Italian bridge of Calamone, on Via Flaminia. Nonetheless, the seamed voussoirs of the ribs and the abutment of an arch in the set of arch stones of an outlet supported by a narrow pier, appear to us to be constructional regulations of Moorish origin. A seam is a constructional device that improves the earthquake-resistant performance of the arch by preventing the voussoirs from sliding, a contrivance that Roman architects were familiar with although they did not apply it very frequently (it appears, for instance, in the wedge-shaped lintels of the theatre in Orange and in the arches on the lower body of the tomb of Theodoric the Great in Ravenna). At a later date this resource was also employed in Moorish construction, as can be appreciated in the Moorish buildings of Andalusia (as, for instance, in the Puerta de Sevilla in the walls of Carmona, and in the Pinospuente bridge in Granada).

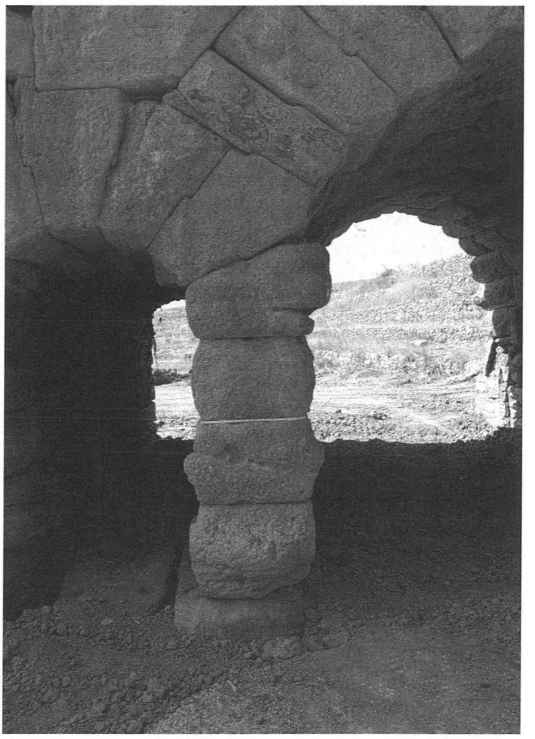


Figure 14
Bridge of Villa del Río

As a constructional composition, the narrow pier measuring 45 cm shared by two vaults with the same number of outlets is too slender for Roman taste. In fact it does not appear in any other Roman bridge, not even in the aforementioned Calamone bridge. Moreover, there is a genuine possibility of it being unstable under certain circumstances, according to the studies undertaken (Durán 1996, 178).

The Los Pedroches bridge also presents seamed voussoirs, and here again, their presence leads us to query the Roman origin of the present stonework, or of a part of it at least, as its three vaults have obviously been reconstructed at a later date, still in the Moorish period, with much narrower voussoirs than those with the seams. In our opinion, both bridges are reconstructions of previous Roman bridges, of which the original foundation and formal layout have been preserved.

Another interesting bridge of ancient appearance, of which only the first courses of rustic work on its piers have survived, is Ponte Ponsul, located some 20 km east of Castelo Branco in Portugal, that stands next to another bridge completed in 1875 during the reign of D. Luis I of Portugal. Studying them some years ago, we reached the conclusion that the presence of rustic work was not sufficient evidence to allow us to classify it as a Roman bridge, in spite of the fact that its erosion denoted age and that it stood along the route of a road possibly linking Mérida-Alcántara-Segura-*Conimbriga* in quite a straight line. The ogival plan of the cutwaters and buttresses, unknown in the Roman bridges in Europe yet a common feature in works of the thirteenth, seventeenth and eighteenth centuries, also made us doubt. However, in a recent trip to Tunisia we visited the ruins of the Roman bridge of Chemtou, over the wadi Mejerda in the ancient city of *Simitthu*, and observed that the cutwaters and buttresses also had ogival plans. Having discovered a genuinely Roman precedent for these initially disconcerting piers of Ponte Ponsul made us reconsider our first opinion and take into account the possibility that the remains discovered did in fact stem from a former Roman bridge.

Another case we have studied in depth is the Roman bridge of Fortanete in Teruel, which has a segmented arch with a span measuring 10.40 m and a width of 3.60 m. The fact that the stonework of this bridge presents two of the features previously described, that is, the rustic work of the voussoirs and the possibility of expressing the two measurements in whole numbers of feet (35 and 20 respectively), not to mention that the flattening of the arch is equal to that of the original arch of the Alconetar bridge, lead us to believe that this is in effect a Roman construction. Nonetheless, the sharpness of the arrises of the voussoirs and of the rustic work, denoting a lack of age, the narrowness of the roadway and the lack of uniformity in the thickness of the ribs raise doubts that cannot be resolved until further research provides conclusive evidence for positive identification.

In northern Portugal we have analysed two bridges pertaining to former Gallaecia, Ponte do Arco da Geia over the river Labruja, near the city of Ponte de Lima, and Ponte do Arco over the river Vizelas, between the cities of Guimaraes and Amarante. The former has an arch with a uniform set of arch stones measuring 60 cm high, eroded rustic work measuring 4.00 m wide

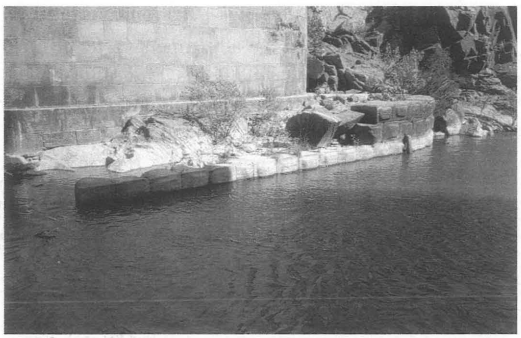


Figure 15
Ponte Ponsul



Figure 16
Bridge of Chemtou

(13.50 feet) and a span of 10.70 m (36 feet). The latter presents two vaults, the largest of which is also the oldest and has a span of 12.60 m (42 feet) and a width

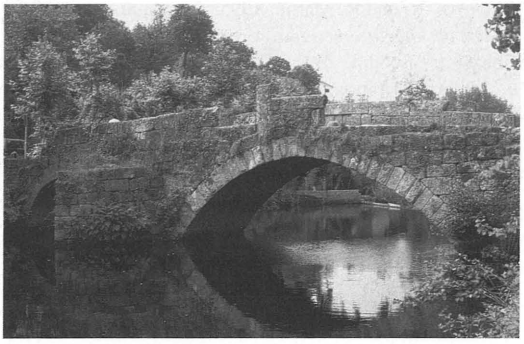


Figure 17
Ponte do Arco

of also 4.00 m, with uniform voussoirs measuring 70 cm and eroded rustic work, while the smaller vault is clearly modern. The fact their most important dimensions are expressed in feet, that the rustic work of the voussoirs is eroded, that no traces made by Mediaeval masons are distinguishable and even that they stand in very Romanised areas close to the *Limia* and *Salacia* mansions respectively, on the route of former road links could tempt us to believe we are before two Roman arches. However, we do not consider these factors to be sufficient to identify the works as Roman, despite clearly belonging to the Roman constructional tradition.

The location of a bridge on the route of a Roman road could be, as in the case of Ponte Ponsul and in the two previous examples, an issue corroborating the Roman origin of a construction. Such is the case of Pontarrón de Los Garabíos, near Valencia de Alcántara, which in addition to being located on a road that possibly linked the Lusitanian *Valentia* and the bridge of Alcántara, has an arcading composed of two equal vaults with spans measuring 8.40 m (28 feet), a width of 4.50 m (15 feet) and some ashlars with rustic work scattered around the present construction built by the Order of Alcántara. It is clearly not a Roman bridge, although we do consider it a legacy of Roman constructional inspiration.

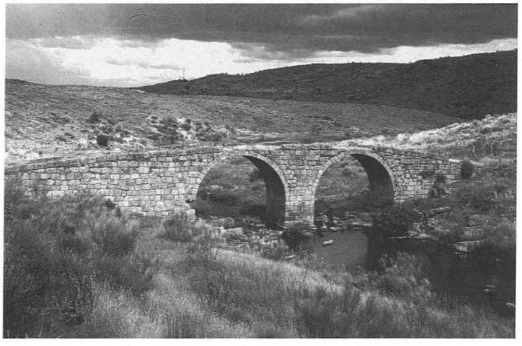


Figure 18
Pontarrón de Los Garabíos

To conclude this essay we shall refer to the remains of a bridge in Pertusa, Huesca, built over the river Alcandre on the route of Road No. 1 on the Antonino Itinerary, and the possibility that these be the only surviving elements of the former Roman bridge. Informed of its existence by the investigator Moreno Gallo, we observed enough characteristics in these remains to harbour no doubts that their origin was in effect Roman —the vault was wide (5.70 m/19 feet), the masonry presented holes to hold the double dovetail cramps, the bond had been carefully executed and the channelling walls on the upstream side have survived, as in the case of the Bridge of the Devil in Martorell, Ponte Navea and Ponte Bibel.

Epilogue

A number of bridges in *Hispania* that have traditionally been regarded Roman should be reconsidered, as the constructional and formal analysis of their stonework would be sure to provide new information leading to a change in attribution. Among other instances, we believe that the stonework in the Luco de Jiloca bridge in Saragosse, the Pollensa bridge in Majorca, the Mantible bridge in La Rioja, the Colloto bridge near Oviedo, the Medellín bridge in Badajoz, the Tardomar bridge in Burgos and the Cihuri bridge over the river Tirón, also in La Rioja, should be the object of detailed examination for, from our point of view, they do not possess sufficient identifying traits nor is there historical data of sufficient substance to confirm their Roman origin.

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Development of composite columns. Emperger's effort

Holger Eggemann

Today's composite columns are made of structural steel, concrete and reinforcing steel. Three basic types of composite columns can be distinguished, completely encased composite columns, Figure 1a, partially encased composite columns, Figure 1b, and filled composite columns, Figures 1d and 1e. Although composite columns were rarely used from the end of World War II until the early 1970's (Viest et al. 1997, 1.13), research had started a long time before, at the beginning of the 20th century. Combining of these materials had a number of motivations, steel columns were often encased in concrete to protect them from fire, while concrete columns were combined with structural steel as a reinforcement.

One predecessor of the completely encased column type was the so called Emperger-Column. It consisted of a cast-iron section embedded in spiral-reinforced concrete and had been used frequently in the construction of high-rise buildings in the United States. The article describes Emperger's activities in the field of composite columns and proves his influence on the construction, which can still be felt today. Another type of today's composite columns, the column with a solid steel core, reminds us of the Emperger-Column and can be considered as successor. It will be proved that Emperger was not only a pioneer in concrete construction, but also a pioneer in composite construction, who tried to link both steel and concrete construction techniques.

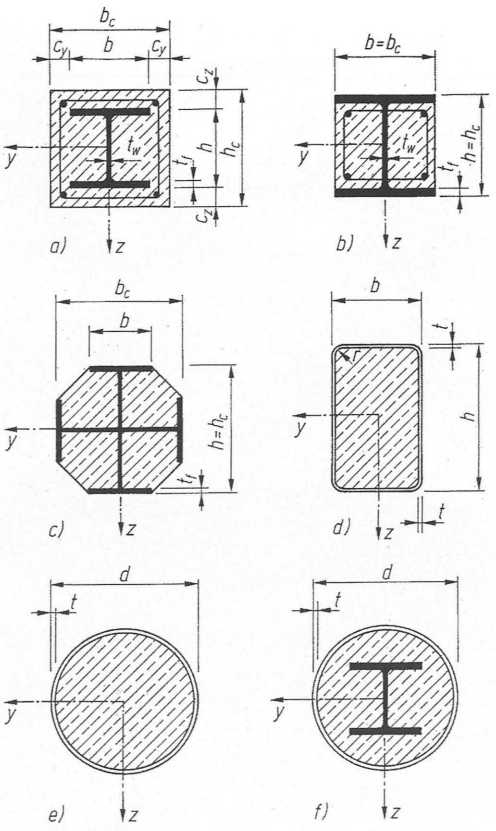


Figure 1
Types of Composite Columns (DINV ENV 1994–1–1, Fig. 4.9)

Fritz von Emperger (1862–1942)

This paragraph is based on a curriculum by Kleinlogel, dedicated to Emperger's 70th birthday (Kleinlogel 1932). Emperger was born on January 11th, 1862 in Beroun (at that time Austria, today Czech Republic).When he began his studies in Prague in 1879, the first effects of Monier's patents had become visible in France and evoked Emperger's interest in the new technology. His first professional activities were in the field of railway and bridge construction. In 1890 he settled down in Chicago as a consultant engineer, where he worked on the planning of New York's and Boston's subways, built the first American concrete bridge in Cincinatti, Ohio and designed high-rise buildings.

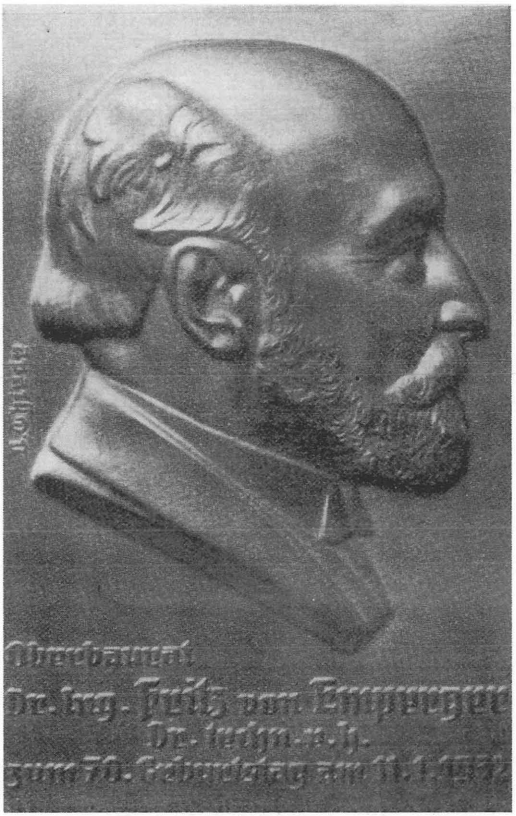


Figure 2
Medal of Honour to Emperger's 70th Birthday (Beton u. Eisen 1932, 50)

After his return to Vienna in 1897, he took his Doctor of Engineering degree in 1903. Previously, he had founded the journal «Beton und Eisen» in 1901, today known as „Beton- und Stahlbetonbau«, since 1906 published by Wilhelm Ernst & Sohn, Berlin. In 1906 he gave the idea to Germany's „Beton-Kalender«, of which he became the editor, and in 1909 he published the «Handbuch für Eisenbeton» with the same company. In 1913 Emperger was honoured by his Majesty, the Emperor of Austria, with the Knight's Cross of the Iron Crown and in the same year received the honorary membership of the British Concrete Institute (Beton u. Eisen 1913, 187, 290). In 1932, after years of intensive research on almost every aspect of reinforced concrete and design and construction of many buildings, he became Doctor honoris causa of Dresden's Faculty of Civil Engineering, Figure 2, and also honorary member of Austria's Committee on Reinforced Concrete (Beton u. Eisen 1932, 50). Emperger died on February 7th, 1942 in Vienna.

Research and Design of Composite Columns

First steps

In the winter of 1901/1902 Emperger started research on concrete columns mostly reinforced with structural steel. For several reasons he had to wait until 1908 to have the specimens tested in Stuttgart with Bach. Although Emperger didn't give explicit evidence for the problems, it can be supposed that there had been internal rivalry with his colleagues in Vienna (Emperger 1908b, Foreword). In 1907, Emperger tested three steel columns to determine their buckling loads (Emperger 1907a). After testing, one of those specimens, Figure 3, was bent back to its original shape by Emperger himself and filled with concrete (Emperger 1907b, 172). Emperger wanted to give evidence for the importance of concrete filling for steel columns. He estimated that the design formula

$$P = \sigma_b (F_b + 15\, F_e)$$

of Prussia's Building Regulations was unsuitable to calculate the ultimate load of a concrete-filled steel column. The number 15 defined the relation between

the modulus of elasticity of steel and concrete. Emperger found out that the ultimate load of a concrete-filled steel column didn't depend on that number.

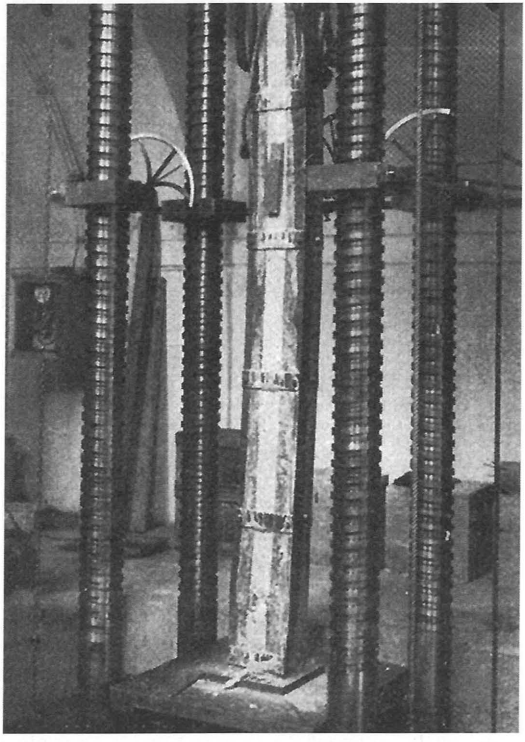


Figure 3
Steel Column filled with Concrete (Emperger 1907b, 173)

Emperger's addition-law

In 1908 Emperger published the results of numerous tests on reinforced concrete columns, among those the specimen tested by Bach (Emperger 1908). Reinforcement was realized by both reinforcement bars and structural steel elements. According to (Gehler 1933, 266), Emperger was the first to verbalise the later well known Addition-Law: „Nach meiner Meinung ist die Bruchlast einer Eisenbetonsäule die Summe zweier Festigkeiten, die von dem Verhältnis der beiden Elastizitätskoeffizienten nicht abhängt» (Emperger 1908, 2). In Emperger's opinion the ultimate load of a reinforced concrete column was dictated by the sum of the strength of both steel and concrete and did not depend on the modulus of elasticity. A design formula of the Addition-Law for reinforced concrete columns was given first by (Mörsch [1902] 1912, 93), with symbols as described in the next paragraph:

$$P = F_b\sigma_b + F_e\sigma_e$$

Emperger's Patent 1911

In 1911 Emperger applied for a Patent claiming «Hohle Gußeisensäule mit einem Mantel aus umschnürtem Beton [Column of hollow cast-iron section encased in hooped concrete]» (Pat. 291068). The spacing of the hooping had to be equal to or less than the thickness of the surrounding concrete shell, Figure 4. Because of an objection from the company Wayß & Freytag A.-G., it took five years until the patent was granted in 1916 (Beton u. Eisen 1916, 47). In 1913 Emperger published a design formula for the ultimate load of such a column:

$$P = F_b\sigma_b + F_e\sigma_e + F_g\sigma_g$$

where σ_g is the compressive strength of the cast-iron in consideration of buckling of the complete section, σ_e is the yield point of the mild steel and σ_b is the compressive strength of the concrete (Emperger 1913, 34). In the same book Emperger reported various test results of encased cast-iron columns. The column sections were varied in many ways, and solid cores were tested too, Figure 5. During the following years, numerous buildings in Austria, Czechoslovakia and the United States had been built with Emperger-Columns, but not in Germany (Kleinlogel 1928, 53). For Kleinlogel the reason had been that Germany's building authorities rejected the application of Emperger-Columns because of missing regulations, and official tests had been refused because of Emperger's patent claim. So in 1928 Emperger decided to give up his claims (Kleinlogel 1928, 53).

Emperger-columns in the United States

In 1915, Emperger gave a report on hooped concrete columns with solid cores at an engineering congress

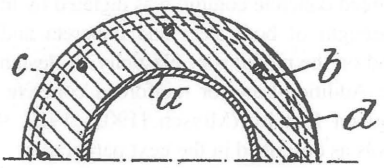


Fig. 2.

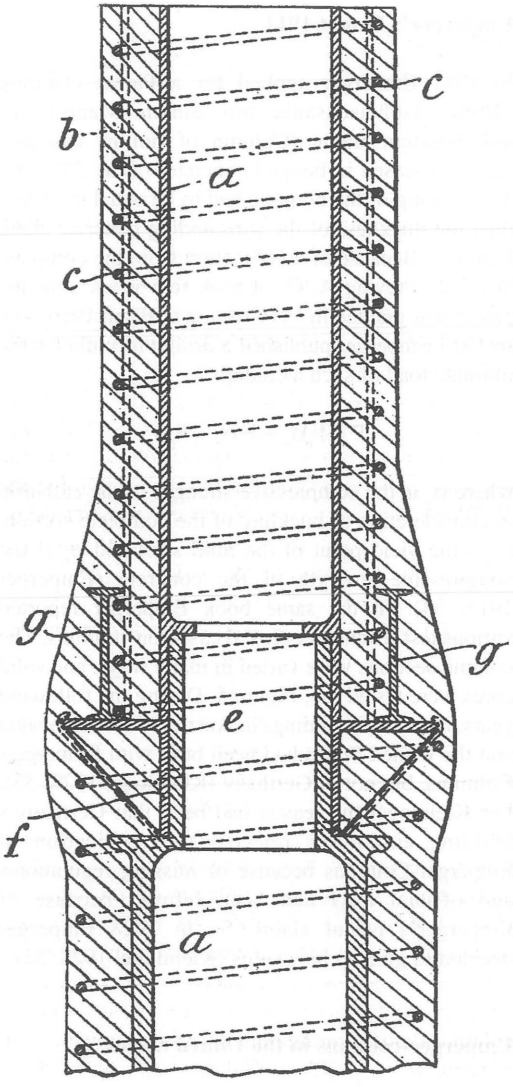


Figure 4
Emperger-Column (Pat. 291068, Fig. 2)

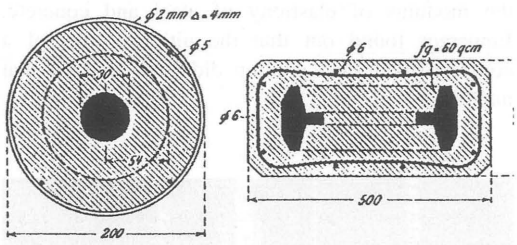


Figure 5
Emperger-Columns with Solid Cast-Iron Cores (Emperger 1913, 53, 56)

in San Francisco, USA. He presented his Addition-Law and pointed out that the strength of the core material was not of great importance, both cast-iron and mild steel were possible. In 1920, Emperger-Columns were regulated in the US Standard Specifications No. 23, Standard Building Regulations for the Use of Reinforced Concrete (ACI 1920). Paragraph 50 stated:

> Composite columns having a cast-iron core or center surrounded by concrete which is enclosed in a spiral of not less than one-half of 1 per cent of the core area, and with a pitch of not more than three inches, may be figured for a stress of 12,000 – 60 L/R, but not over 10,000 lb. per sq. in. [69 N/mm≈] on the cast-iron section and not more than 25 per cent of the compressive strength . . . on the concrete within the spiral or core. The diameter of the cast-iron core shall not exceed one-half of the diameter of the spiral (ACI 1920, 302).

Emperger's Addition-Law was applied in a modified form, using a specified Tetmajer-Formula. This was the first official building regulation for Emperger-Columns. The maximum allowed compressive strength of the concrete was 3000 lb. per sq. in. (20.7 N/mm≈), so a column could be calculated with a maximum stress on the concrete of 4.1 N/mm≈. In 1928 the paragraph was amended and cores of mild steel were permitted too (ACI 1928, 824). This building regulations made it possible to use Emperger-Columns in the design of many high-rise buildings in the United States, above all in Chicago:

> Buildings having the Emperger type of column, . . . include the following: Surf-Hotel, Chicago, eleven storeys; two sixteen-storey apartment buildings at

3730–40 Sheridan Road, Chicago; Aragon Hotel, Chicago, twelve storeys; Krolick Department Store, Detroit, 150˝200 ft. [46˝61 m], twelve storeys, with column loads of 2,000,000 lb. [9 MN], and a building of the same size for the Detroit Pressed Steel Company. Of these, the Surf Hotel and the Krolick Store have hollow cast-iron cores (ENR 1930, 278).

Two other buildings in Chicago had been mentioned before, the 16-storey McGraw-Hill Building, see Building Case Histories, and the 30-storey Trustees Building, also known as Corn Products Building. In 1930 test results on composite columns were published by (Mensch 1930). Tests were made for the new Building Code Committee of the City of Chicago to verify Emperger's results under American conditions. Mensch figured out «that Dr. Emperger's claim of the strength of the composite column being greater than the sum of its components has been verified by every test» (Mensch 1930, 270).

Composite Columns in Europe

Emperger complained several times about the lack of building regulations for composite columns in Europe. «Für die beiden . . . Säulenformen bestehen in keinem europäischen Staate Vorschriften [There are no regulations for these two types of columns in any of the European countries]» (Emperger 1931a, 265; similar 1930, 1931b). Emperger meant the encased steel column and his own type. At the First Congress of the International Association for Bridge and Structural Engineering in Paris in 1932, Emperger mentioned more than 1000 tests on composite columns in Europe and about 570 in North America. He distinguished four different types of composite columns, Figure 6. Type I was called structural steel column with concrete core, Type II was a steel column encased in reinforced concrete with lateral ties, Type III was called steel column encased in strongly hooped concrete, the Emperger type, and Type IV was a steel column with slight hooping. Type I and Type II are in use today, of course with modern types of structural steel elements. Type I now is called partially encased composite column and Type II is known as completely encased composite column. Columns with spiral reinforcement are neither used in concrete nor in composite construction today.

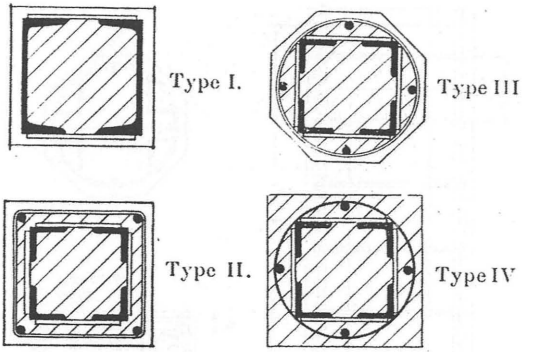


Figure 6
Composite Columns 1932 (Emperger 1932, 596)

In 1931, Rudolf Saliger, Professor at Vienna University, reported several test series on composite columns of the Bauer-Type (Saliger 1931; Bauer 1930). These Columns were examined as an alternative to steel or concrete columns in two high-rise buildings in Vienna. Saliger can be considered Emperger's rival, as he strictly avoided calling Emperger's name in his article. Later on, Emperger had a dispute with Saliger about the application of the Addition-Law (Bauingenieur 1931, 656). During the 1930's, additional tests in Germany were made by (Memmler, Bierett and Grüning, 1934) on steel columns filled with conrete and by (Gehler and Amos, 1936) on concrete columns reinforced with structural steel. The latter ones led to the first German building regulations on composite columns. They were passed in 1943 (DIN 1045–1943). §27 d) dealt with concrete columns reinforced with structural steel, Figure 7. This paragraph existed until 1972, when the design of reinforced concrete columns was based on the ultimate load theory, and officials decided that structural steel members encased in concrete should be designed to carry the loads alone without considering the strength of the concrete (Bonzel, Bub and Funk 1972, 49). But lack of steel during war and post-war period prevented the use of composite columns in Germany. In fact, engineers were instructed to save steel by using concrete columns with a minimum of reinforcement: «zur Einsparung von Stahl . . . Säulen . . . zu wählen, deren Bewehrungszahl μ in der Nähe der unteren Grenze liegt» (DIN 1045–1943, 21).

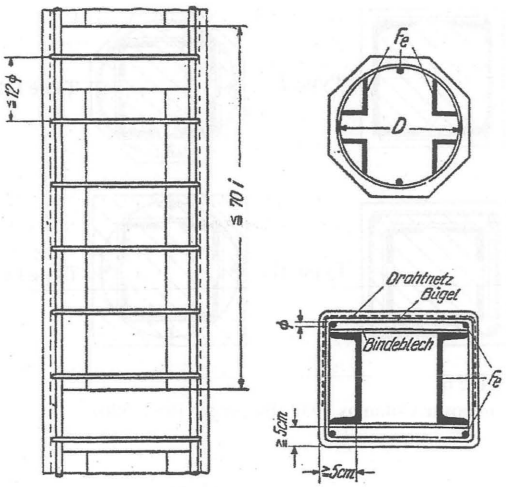


Figure 7
Concrete Columns reinforced with Structural Steel (DIN 1045–1943, Fig. 23)

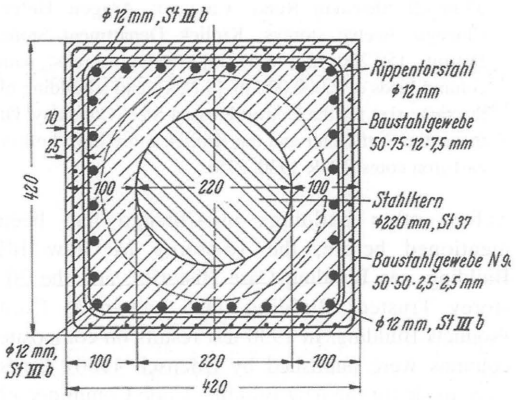


Figure 8
Composite Column with Solid Steel Core (Boll and Vogel 1969, 260)

Composite columns with solid steel core— Successor of the Emperger-Column

In 1965 Boll applied for a patent claiming a column with a solid steel core, with its core bearing the load and the surrounding concrete shell providing buckling safety and fire protection (Off. 1559482). Later in 1969 he tried to execute such columns in a high-rise building in Hamburg. Lack of time prevented the approval by building authorities, meaning the building had to be constructed with regular columns (Boll and Vogel 1969, 259). The connection to Emperger's column is obvious. A solid core is surrounded by reinforced concrete, preventing the core from buckling. Strong hooping is provided too. Lateral reinforcement was to be realized using bars of 12 mm, spacing 7.5 cm, Figure 8. This type of column was first realised in 1976 in a hospital in Vienna (Krapfenbauer 1976). There are two recent examples of buildings with steel core columns, one is a high-rise building in Cologne, the so-called «Kölnturm», where steel core columns were used in the lower floors. The other is the Millenium-Tower in Vienna, completed in 1999. Because of Emperger's connection to Vienna, this building will be described in paragraph Building Case Histories. Today, this type of column lies within the scope of Eurocode 4.

Simplified Design Method of Eurocode 4 for Composite Columns

The simplified design method of Eurocode 4 is based on the method developed at Bochum University by (Roik et al. 1976). Similar to Emperger's Addition-Law, the ultimate load of a composite column is:

$$N_{pl,Rd} = A_a f_{yd} + A_c \alpha_c f_{cd} + A_s f_{sd}$$

where f_{yd} is the yield strength of the structural steel, f_{cd} is the compressive strength of the concrete and f_{sd} is the yield strength of the reinforcing steel. Buckling safety is provided by a factor k, by which the ultimate load has to be multiplied. The factor k is given by European buckling curves of Eurocode 3. It has to be calculated as a function of the non-dimensional slenderness $\overline{\lambda}$.

An even more simplified design method for composite columns for the specific needs of architects and structural engineers during pre-dimensioning was developed at Aachen University by (Eggemann 2002). It determines the factor k as a function of the slenderness ratio L/R, where L is the length of the column and R is the effective radius of gyration. Furthermore, numerous means are provided to calculate the effective radius of gyration of a composite column with the radius of the steel section multiplied by a correction factor a.

Building Case Histories

The application of composite columns, especially of the Emperger type, is illustrated in this paragraph by two old buildings and one recent example.

McGraw-Hill Building, Chicago 1929

Architect: Thielbar & Fugard, Chicago
Engineer: James B. Black, Chicago

The McGraw-Hill Building in Chicago, Figure 9, was built in 1929. It was 30 to 38 m (100 to 125 ft.) in plan and 58 m (190 ft.) high with 16 storeys over ground, confer to typical floor plan, Figure 10. Emperger-Columns were used with a solid core of cast-iron:

> Cored Concrete Columns—To conserve space the designers adopted a composite column known as the Emperger type, in which the use of a solid cast-iron core permits a relatively small cross-section. The core is supplemented by the usual vertical bars and spiral reinforcement (ENR 1929, 129).
>
> In designing the McGraw-Hill Building, the columns were made of uniform section (24 and 26 in. square [61 and 66 cm]) from basement to roof for economy, convenience and rapidity in construction . . . The variation in carrying capacity was obtained by reducing the cast-iron cores gradually from 12fl to 3 in. [32.4 to 7.6 cm] in diameter. For the upper floors, where cores were not needed, standard hooped concrete was used (ENR 1930, 277).

A special detail of a column joint was developed, Figure 11. The cores were milled to be truly square with the axis. Each core extended 5 in. (12.7 cm) above floor level, then a pipe sleeve was placed over the core. The pipe was filled with grout and the next core was set into the pipe, adjusted and fixed in the formwork before the conrete was poured.

One curiosity has to be mentioned: In 1998 the building was demolished and by 2000 it had been



Figure 9
McGraw-Hill Building, Chicago 1929 (ENR 1929, 129)

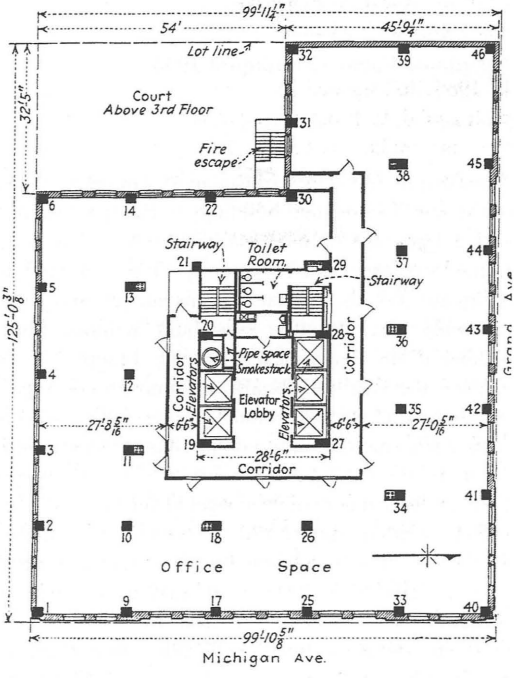


Figure 10
Typical Floor Plan, McGraw-Hill Building (ENR 1929, 130)

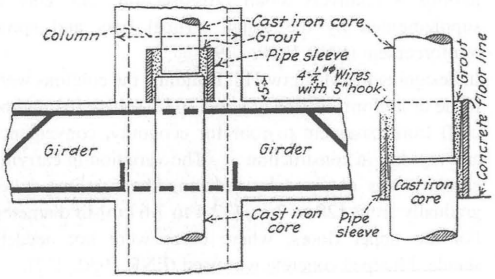


Figure 11
Detail of Column-Joint in McGraw-Hill Building (ENR 1929, 130)

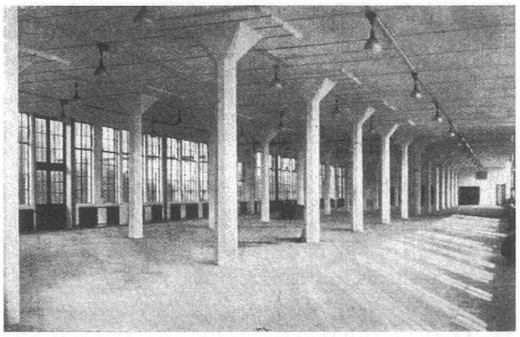


Figure 12
View in First Floor of Telephone-Factory, Budapest (Enyedi 1931, 244)

rebuilt with the original facade attached to a new structure. The feat was demanded by preservationists and City Hall. The lower part of the building now contains a shopping mall, where one can see large Lego models of the building itself and five others, e.g. Chicago's Sears Tower and John Hancock Center (skyscrapers 2002).

Telephone-Factory, Budapest 1930
Architect: N. N.
Engineer: Béla Enyedi, Budapest

The Telephone-Factory in Budapest, Hungary, is one of the few documented buildings in Europe designed with Emperger-Columns. Built in 1930, it has got a framed structure with a column spacing of about 5,60 m square. For the reason of transparency and cable assembly, the structure was built without floor-beams, using flared heads instead, Figure 12. To achieve the smallest possible column proportions—the company wanted columns of less than 40 cm square with the option of adding another storey—the columns were designed according to the Emperger type, but with a core of mild steel instead of cast-iron: «[Es] wurden umschnürte Stützen mit steifen Flußeiseneinlagen, System Dr. Emperger, gewählt» (Enyedi 1931, 242). The columns were made of octagonal sections, 39 cm in view, and with a strong hooping (spiral reinforcement). The columns on the basement, made of ordinary reinforced concrete, 66 cm square, had more than double the cross-section area, Figure 13.

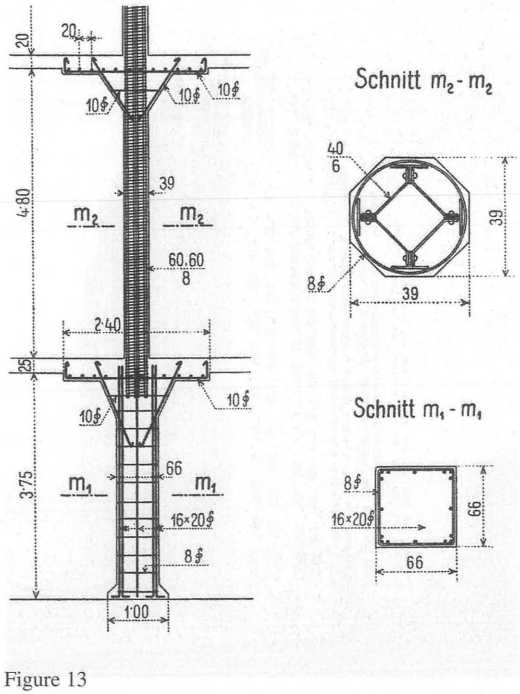


Figure 13
Column Section of Telephone-Factory, Budapest (Enyedi 1931, 243)

Millenium-Tower, Vienna 1999
Architect: Peichl, Podrecca and Weber, Innsbruck
Engineer: Tschemmernegg, Obholzer and Baumann, Innsbruck

The 50-storey Millenium Tower in Vienna is the tallest building in Austria, with a height of 202 m, Figure 14. After construction had been started in 1998, it took less than one year until its completion in 1999. The structure consists of a reinforced concrete core, while composite construction was used for the ceilings and columns in the office areas (Tschemmernegg 1999, 607). The exterior columns are made of conrete filled hollow sections with solid steel cores, Figure 15. The columns themselves have a diameter of 406.4 mm from first to 14th floor and 323.9 mm above. The cores were gradually reduced from 220 mm to 85 mm, and above the 39th floor no cores were needed. Eurocode 4 was used for the design of both structure and fire-resistance. Shear connection between concrete and structural steel was realised by special nails.



Figure 14
Millenium Tower under Construction 1999 (Tschemmernegg 1999, 610)

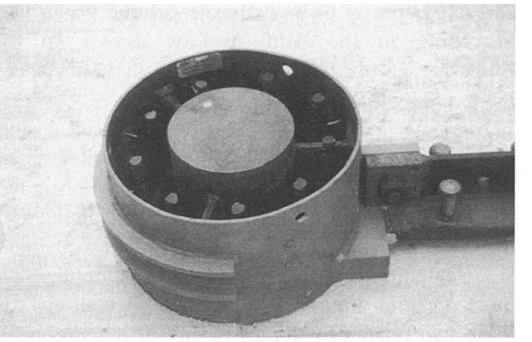


Figure 15
Composite Column with Solid Steel Core, Millenium Tower (Angerer, Rubin and Taus 1999, 642)

Abstract and Conclusion

During the first half of the 20th century a lot of research was done on composite columns. The combination of materials had different motivations, steel columns were often encased in concrete to protect them from fire, while concrete columns were combined with structural steel as a reinforcement.

In 1911 the Austrian engineer Fritz von Emperger (1862–1942) applied for a patent on the later so-called Emperger-Column, granted in 1916. This column was made of a hollow cast-iron section embedded in spiral-reinforced concrete. Until the 1930s, this type of column had been used in several buildings in the United States, one of them beeing the 30-storey Trustees Building in Chicago. In the Krolick-Warehouse in Detroit, columns reached a load-bearing capacity of 9 MN.

In 1932 Emperger gave a report on composite columns at the First Congress of the International Association for Bridge and Structural Engineering. He mentioned more than 1500 tested specimens in Europe and North America, among those were 138 tests done by himself. Emperger classified four different types of composite columns. The load

carrying capacity of a composite column was given according to the Addition-Law drawn up by Emperger, as the sum of the strength of the steel increased by that of the concrete.

Emperger complained about the lack of design rules for composite columns in Europe. He mentioned the American building regulations, which gave explicit formulas for both the Emperger-Column and the steel column encased in concrete: «Für die beiden . . . Säulenformen bestehen in keinem europäischen Staate Vorschriften [There are no regulations for these two types of columns in any of the European countries]» (Emperger 1931, 265). The research program of (Gehler and Amos, 1936) led to the first german building regulations for composite columns, defined in the German code for reinforced concrete, DIN 1045, in 1943.

It can be said that Emperger was not only a pioneer in concrete construction, but also a pioneer in composite construction. Emperger's influence on the construction is obvious. His Addition-Law can still be found in the design method of today's Eurocode 4, and the composite column type of an encased solid steel core used e.g. in the construction of Vienna's Millenium Tower, reminds us of the so-called Emperger-Column and can be accounted to be its successor.

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Construction history of the composite framed tube structural system

Richard A. Ellis
David P. Billington

This paper examines the construction history of tall buildings designed during the latter portion of the twentieth century. Fazlur Khan was able to capitalize on the inherent strengths of steel and concrete by using them in conjunction with a framed tube system. This idea involves a novel construction process, which takes advantage of the virtues of structural steel and reinforced concrete. Early applications of this system in the mid-1960's were in the 35–story Gateway III Building in Chicago, Illinois and the 25 story CDC Building in Houston, Texas. Composite construction is now being used more frequently in the design of high rise buildings. This paper will look closely at the construction history of the 52–story One Shell Square Building in New Orleans, which was completed in 1971 and still stands as the tallest composite building in the world, at 700'. In One Shell Square, light steel framing is erected first. Temporary stays are used to position the steel members and then left in place for lateral resistance in the exposed steel frame. Placement of concrete filled metal deck follows closely behind erection of structural steel. Placement of rebar cages and forms around the perimeter steel columns and spandrels follows erection by 6 to 8 floors. Concrete is then cast to form a solid concrete tube around the light steel frame. The resulting structure has 40' of rentable floor space and minimal foundation requirements due to the light steel frame. The concrete perimeter provides exceptionally high lateral resistance, some thermal insulation, and a degree of fire protection for the primary lateral structural system. As a result, the potential applications for composite construction are numerous, especially with the renewed awareness of fire protection concerns in high-rise structures.

Study of such innovations allows us to see how they came into being, how individual engineers contributed to their success, and how the local construction constraints stimulated the search for such new ideas.

Introduction

Born in Dacca, Bangladesh, Fazlur Rahman Khan received his Bachelor of Engineering degree from the University of Dacca. Khan then taught at the University of Dacca for two years before coming to the United States. He studied at the University of Illinois, Champaign/Urbana, where he earned MS degrees in structural engineering and theoretical applied mechanics and a Ph.D. in structural engineering. Immediately after receiving his Ph.D. in 1955, Dr. Khan joined the Chicago office of the architectural/engineering firm of Skidmore, Owings & Merrill (SOM) and was made a general partner in charge of structural engineering in 1970. While working with SOM, Dr. Khan also taught and served as a research advisor at the Illinois Institute of Technology (IIT).[1]

Fazlur Khan introduced a series of innovations that changed the way engineers' viewed tall concrete

building structures. He could not have done this without the close collaboration with his partners and colleagues at Skidmore, Owings, and Merrill. Especially the architect Bruce Graham and the architect-engineer Myron Goldsmith were crucial to Khan's success. Also there were excellent structural engineers who worked with him, most prominently Hal Iyengar and John Zils. Khan was also fortunate to be able to work closely with developers and builders as he thought through his new ideas. Fazlur Khan's experience of working with developers and builders allowed him to develop new systems. The resulting structures, which integrated engineering and construction practice, could be built economically. He died in mid-career with many plans uncompleted but he nevertheless achieved the status of structural artist whose works will be studied long after the twentieth century.[2]

Structural Tube System

In 1961, Dr. Fazlur Khan began to seek structural systems that would allow for construction of taller buildings without paying the «premium for height» which resulted from the wind loadings. He recognized that overcoming this premium would require new systems and new construction practices, in the tradition of the technology-oriented style commonly referred to as the Chicago School of Architecture.[3] This led him to the creation of the framed-tube, in which exterior closely spaced columns and deep spandrels provide the entire lateral resistance. The World Trade Center employs this scheme on a grand scale. The exterior columns have narrow spacing and the windows are recessed, creating the illusion of solid tubes.

Khan first used the framed-tube in the 43–story DeWitt Chestnut Apartment Building in Chicago, completed in 1965. Here, perimeter columns are spaced at 5.5 feet on centers and the spandrels between columns at each level are about 2 feet deep. The close column spacing expresses the idea of a solid tube perforated by holes that create the windows.

Structurally, the framed-tube is superior to a rigid frame because it places material on the exterior of the building, where it will contribute most to the moment of inertia and maximize the lateral stiffness of the building. The DeWitt Chestnut Building also has a relatively small floor plan, so by moving the lateral system from the core to the exterior of the building valuable floor space is freed. The entire interior structural system is secondary —designed to carry only gravity loads to the ground level.

In 1963 Khan started to contemplate a new system in which lateral forces were carried primarily by an interior shear wall core. The resulting 38–story Brunswick Building in Chicago was designed with a substantial concrete shear wall core. Much of the building's service machinery were also located in the core. Perimeter columns were placed at 9 feet 4 inches on centers and tied by deep spandrel beams at each floor. In making a quick check of the design calculations it became evident to Khan that the exterior framing was nearly as stiff as the shear wall core acting as a vertical cantilever.[4]

Khan had created an efficient system in which lateral loads are carried both by the exterior frame and interior shear wall core through shear wall-frame interaction. According to Khan, «One of the advantages of the shear wall frame interaction system is that it exists in every reinforced concrete building with shear walls, whether the frame is deliberately designed for it or not, simply because every joint in a reinforced concrete structure when cast monolithically acts as in a rigid frame».[5] In the Brunswick Building, this system also created 38–feet of unobstructed space by allowing the interior columns all to be placed in the building's core.

Composite Construction

By employing various structural systems in buildings of steel and buildings of reinforced concrete, Khan was able to gain a clear sense of the advantages and disadvantages of each material. He then developed a system to take advantage of a steel structure combined with one of a reinforced concrete. This is the basis for what became known as the SOM-Composite System.[6]

For framed tube structures the system consists of an exterior frame in reinforced concrete. The interior floor framing is erected entirely with structural steel. Concrete offers properties for inherent fire protection with out resorting to the separate cladding used in fire protected steel surfaces. Under normal service

the concrete tube will serve as a layer of insulation causing a reduction of heating and cooling loads. The lateral stiffness of the concrete tube is often adequate to carry the wind loads, while the steel floor framing carries most of the gravity dead loads, except for the weight of the concrete tube itself.

This also avoids the disadvantages of concrete construction. Namely: interior concrete shear walls contribute greatly to the loss of floor efficiency and concrete construction is typically much slower than steel erection. In most high-rise structures, floor framing contributes to 75–80% of the total material in the structure.[7] Composite construction practices can result in construction cycles that are as fast as structural steel erection, demonstrated first in the 50–story CDC Building in Houston, Texas where the entire steel frame for five stories was erected before concrete casting commenced. This separated the two work forces necessary for the two materials and allowed a fast construction pace. Precast modular window framing units were attached during steel erection and then used as forms for the casting of the exterior concrete frame. The construction cycle was 3 days per floor for all 50 floors. Khan designed similar composite construction projects at One Shell Square in New Orleans and Union Station in Chicago where construction cycles ere on par with those for steel erection. Since normal concrete construction cycles can be in excess of 7 days per floor, the savings in time allowed by composite construction reduced cost as much as 33%.[8]

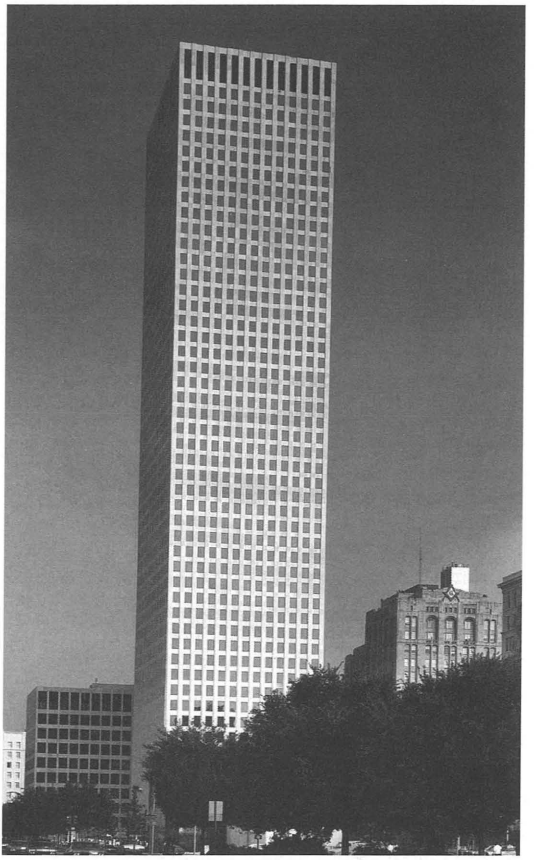


Figure 1
Facade of One Shell Square, New Orleans

One Shell Square

Completed in 1970, One Shell Square remains the tallest building in New Orleans at 52 stories. Fazlur Khan designed it for the developer Gerald D. Hines. One Shell Square is most interesting from a structural perspective because of innovative use of steel and concrete. The composite system that was developed by Khan is efficient because it capitalizes on the inherent strengths of each material. Material selection was driven by a desire to maximize the rentable floor space and overall stiffness under lateral loads while minimizing the dead weight and total cost per area of the building.

One Shell Square was designed with a composite structural system that combined steel floor framing and a steel core with concrete encased steel columns on the periphery of the building. Efficiency was gained through the use of steel in the floor frame because the ductile metal is approximately 9 times stronger than concrete and has a higher modulus of elasticity (29,000 ksi for steel vs. 3,200 ksi for concrete) so more compact sections could be used to achieve the same strength. Compact sections are essential in steel frame design because steel is a very dense material. However, well-designed steel floor beams are able to span long distances. In One Shell Square the floor-framing scheme allowed for 40' of column free space around the buildings braced steel core. Steel floor framing was also desirable because it could be erected quickly when compared to a

concrete frame.[9] The World Trade Center Towers were marvelous examples of a framed tube made entirely of structural steel.

In very tall buildings, like One Shell Square, lateral loads dictate design. Lateral loads can result from seismic activity like an earthquake but in New Orleans the critical lateral loads applied to structures are wind. Structures must be designed with adequate stiffness to counteract the overstressing moment resulting from wind. A high premium would have to be paid for the additional material to stiffen a steel structure of this height. In the World Trade Center mass tuned dampers were used at each story to minimize lateral sway from wind, which contributed to the structure's $700 million price tag.

The use of reinforced concrete on the perimeter of One Shell Square allowed designers to overcome this premium. The stiff concrete columns and spandrels formed a braced tube, which provided lateral resistance for the entire structure. A concrete framed tube is ideal for composite systems because it places large heavy sections on the perimeter of the building, as far as possible from the centroid, where they will contribute most to the moment of inertia of the structure. The moment of inertia, modulus of elasticity, and unbraced length determine the stiffness of a structure. The perimeter composite columns of One Shell Square have a close spacing of 10'. This gives the spandrels a shorter unbraced length, further stiffening the structure against lateral loads.

Construction Sequencing

The construction sequencing of One Shell Square was an most innovative aspect of the composite design. Steel erection and concrete casting had to be kept separate if they were to occur on the same site. Each requires a specialized labor force and equipment. Interference between the two could cause complications and result in delays. To avert this problem construction of One Shell Square began with traditional steel frame erection.

Steel sections were positioned using temporary $^3/_4$" cable stays. The stays were left in place during construction of the steel frame to provide additional stiffness to the compact sections. In this initial phase the braced core carried all lateral loads so the perimeter columns were sized to carry minimal gravity loads. The largest steel section used on the perimeter was W8 × 67, which can be compared to the large W14 × 550 and built-up sections used in the core of the structure. Figure 2 shows the dimensions of one built-up column at the base of the structure. The core was stiff enough to allow erection of 10 to 12 stories of exposed steel. Placement of metal deck and casting of the floor slab follow closely behind erection of the frame.

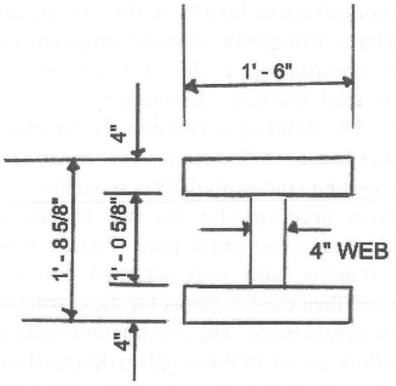


Figure 2
Construction detail of One Shell Square steel perimeter column

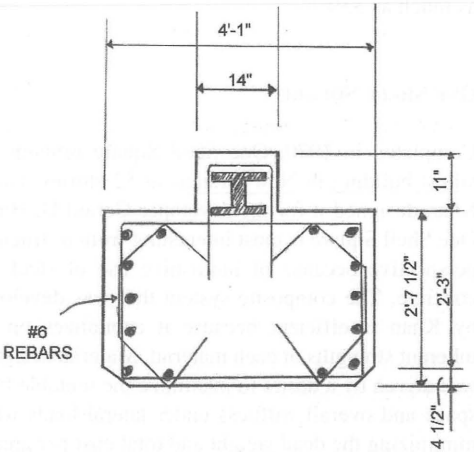


Figure 3
Construction detail of One Shell Square composite perimeter column

Once steel erection had progressed to a prescribed height of 9 stories, concreting of the building's perimeter began. Rebar cages and forms were attached directly to the exterior steel frame sections. Concrete was then poured into the forms, completely encasing the exterior light steel frame (Figure 3). Composite action begins once the columns become monolithic with the floor slab and spandrels. Casting of concrete and steel erection then proceeded simultaneously until both reach the completed building height of 52 stories.

Structural Analysis

The efficiency gained by the composite system can be easily observed through an analysis of the construction sequence. Construction was divided into 5 phases in order to identify critical points in the sequence. SAP2000 was used to create a 2–D model of the structure. Figure 4 shows the proportions of the SAP models that were used for the 5 phases of construction. The section properties and dimensions for the columns used in each model appear in Table 1. The model takes the equivalent moment of inertia, cross-sectional area, and dead weight from one bay of the buildings frame and applies them to a planar frame with equivalent properties.

The effective area of one bay is outlined in Figure 5, which shows the actual floor-framing plan for One Shell Square. Each construction phase was subjected to a combination of wind, dead, and live load. The output, however, has been formatted to show the building's response from each load separately. In this manner, it can be determined which load must have governed design. As expected the building's response to wind load was the most critical, so that is what is discussed here.

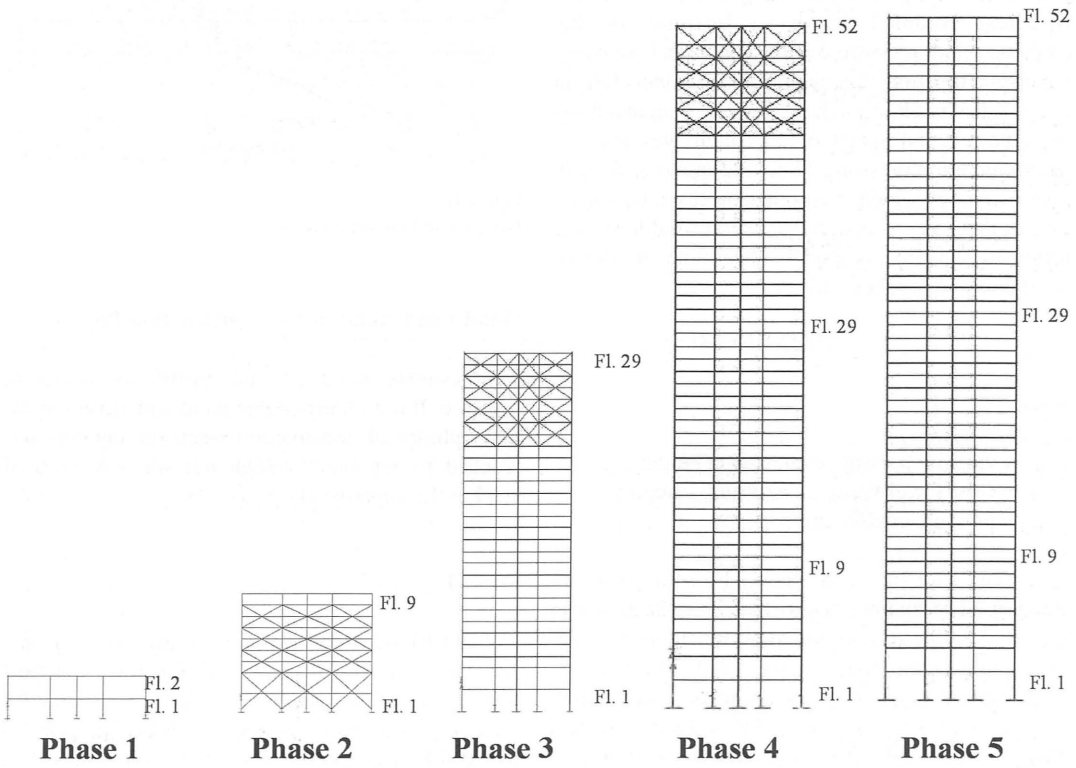


Figure 4
One Shell Square construction phases

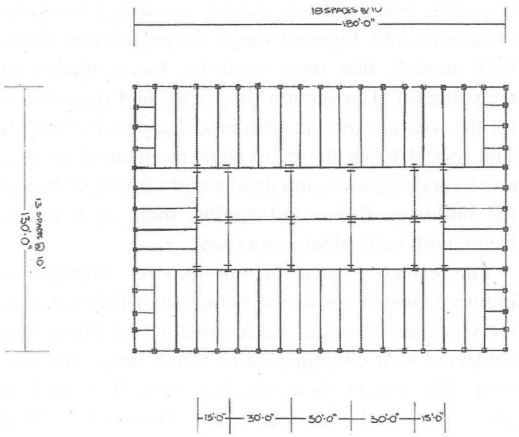


Figure 5
One Shell Square floor framing plan

The wind pressure profile used in this analysis was generated using the method prescribed by the American National Standard's Institute. In this method, wind pressure varies with wind velocity, which is a function of elevation. New Orleans falls in a region that is subject to hurricanes on a regular basis so a basic wind speed of 140 mph was used to determine wind pressure. The wind pressure for any given story was then multiplied by the total facing area of that story to obtain the design wind load. The following equation is used to determine the design wind pressure at all elevations;

$$p = q_z G C_f$$

where:

q_z = velocity pressure evaluated at height z
G = Gust factor based on exposure category
C_f = pressure coefficient

A gust factor (G) of .8 was used for this exposure category. The number is less than 1, indicating that the surrounding terrain will probably reduce, rather than amplify, the effect of the wind. The pressure coefficient C_f is based on the inclination of the roof. A value of 1 was used here. The velocity pressure changes with height. It is based on the expression:

$$q_z = .00256\, K_z V_x^2 I$$

where:

K_z = velocity pressure exposure coefficient
V_x = mean wind speed at roof height
I = importance factor

The mean wind speed at roof height was 140 mph. The importance factor was 1.0 for this multi-use structure and the velocity pressure exposure coefficient varied with height between .32 and 1.46. At the 29th story a K_z of 1.12 was used, resulting in a design pressure of 44.96 psf.

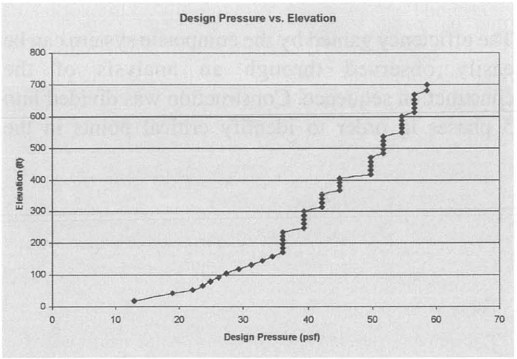


Figure 6
Design wind pressure profile

Wind Load Analysis for Construction Phases

The resulting wind pressure profile is shown in Figure 6. It is anticipated that wind will govern in the latter phases of construction when the building has reached its maximum height but still has exposed steel in the upper levels.

Phase 1

The first phase analyzed considers two floors of steel framing under wind, dead, and live load. Figure 7 shows a free body diagram of Phase 1 under wind load only. A joint on Column Line B has been circled in red. Moment equilibrium for this joint is checked in Figure 8. Note that the core columns (with the exception of the central column, which carries none

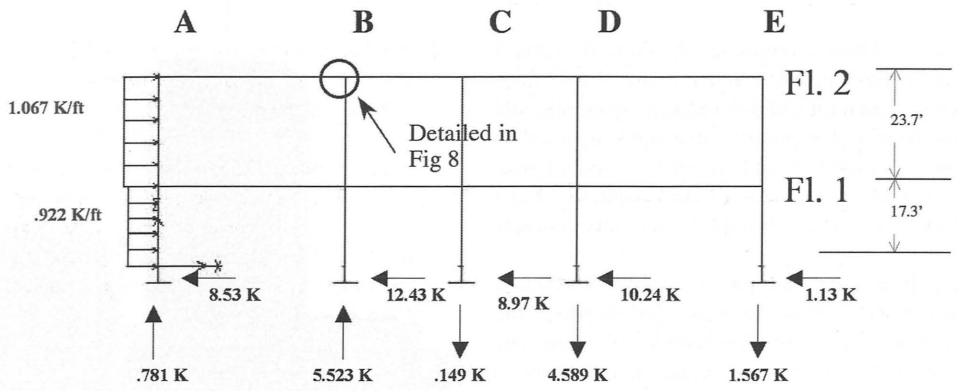


Figure 7
Construction phase 1 wind load analysis

of the wind load as an axial force) take a larger portion of the axial and shear load due to their high stiffness. The stiffest members will attract the greatest proportion of the load. In this early phase of construction design wind pressure is small and the height of the structure is low so the member stresses and displacements are well within the acceptable range for the material. Floor 1 has a height of 17.33' and Fl. 2 has a height of 23.73. The resulting horizontal wind load is then:

$$(1.067\ \text{K/ft} * 23.73') + (.922\text{K/ft} * 17.33') = 41.3\ \text{K}$$

This is equal and opposite to the sum of the horizontal reactions:

$$(-8.53\text{K} - 12.43\text{K} - 8.97\text{K} - 10.24\text{K} - 1.13\text{K}) = -41.3\text{K}$$

So that:

$$\Sigma F_x = 41.3\ \text{K} - 41.3\ \text{K}$$

The structure does not project a large area to the wind with only 2 floors of exposed steel framing erected so it is not surprising that the deflections are very small. For tall structures The Uniform Building Code dictates that the lateral deflections must be less than L/360; where L is the total height of the structure. The floors in Phase I have a total height of 43.06 ft. so L/360 for this structure is 1.44 in. The actual maximum deflection is .1407 in. at joint 11. 55 ksi steel was used in the construction of One Shell Square. All the stresses are in the elastic range under this load.

$$\Sigma M_z = M_1 + M_2 + M_3$$
$$= (-3.19 - 34.4 + 37.4)\ \text{K-ft}$$
$$\approx 0$$

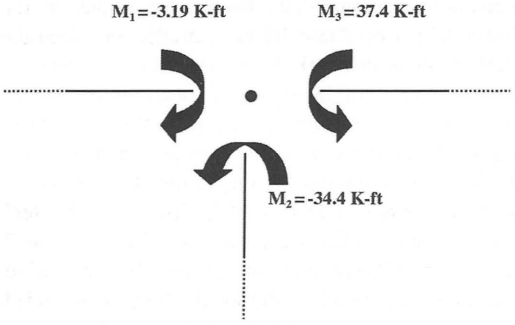


Figure 8
Moment equilibrium for joint in phase 1

Phase 2

Construction Phase 2 represents the limit of exposed steel erection in One Shell Square. After the 9th floor is erected, concreting of the external spandrels and columns begins. Temporary cable stays are used to position steel members and stiffen the exposed steel structure under lateral loads. Floor 3 of Phase 2 has a height of 13'. Floors 4 through 9 each have a height of 26'.

Phase II is a critical phase in the construction sequence because it is the phase during which the maximum amount of steel has been left exposed. The temporary cable stays are essential at this point to limit lateral deflections under the wind load. The lateral deflections of the columns are greatest in the windward columns and decrease slightly with increasing distance from the windward face. Phase II is 134 ft tall. L/360 is slightly less than 5 inches for this phase. A maximum horizontal deflection of 1.48» at the 9th floor occurred in Phase II. This is acceptable. The vertical deflections under wind are practically negligible



Figure 9
Construction photo of One Shell Square (phase 3)

Phase 3

Phase 3 signifies the point at which the structure begins to behave like a composite tube. Construction Phase 3 is a 29–story model of the building.

Figure 9 is a photograph of One Shell Square that was taken during this phase of construction. It is evident that the columns and spandrels of the bottom 21 floors have been encased in concrete and act as composite sections with large cross sectional area and moment of inertia. The resulting structure is stiffer than the first two phases, however the top 7 stories are exposed steel frame. This creates a more critical scenario than Phase 2 because the least stiff members in the system, the exposed steel frame, are at the top of the structure where wind loads are largest.

The reactions at the base of the structure reflect the high stiffness of the exterior columns. While the elastic modulus of concrete is less than that of steel, the moment of inertia of the composite perimeter columns is far greater than any of the other columns. The stiffer columns attract more of the lateral load in this framed tube. The fl» cable bracing becomes essential in this phase to limit deflections and insure that the structure remains safe in its vulnerable state. The equations of equilibrium can once again be used to verify that the base reactions are equivalent to the external wind load that has been applied to the structure. The vertical reactions due to wind load become more complex to calculate in this phase because the section properties of the columns vary greatly between the top and bottom of the structure.

One Shell Square begins to act like a composite tube at its base in Phase III. This is evident in the structures response. The lateral deflections in the lower levels of Phase III are actually less than the deflections in Phase II. At the second level, Phase III had a maximum horizontal deflection of .63 in., which can be compared to .72 in. in Phase II. Phase III is also a taller structure and projects a greater area to the wind so the overturning moment at the second level in Phase III (1,567.49 kip-ft) is nearly three times as large as the overturning moment in the same location in Phase II (554 kip-ft). The maximum deflection at Level 9 in Phase III was 1.61 in., which can be compared to 1.48 in. for Phase II.

In Phase II this deflection results from a bending moment of only 25 kip-ft, while in Phase III the

structure is responding to a moment of 575 kip-ft. The stiff behavior in Phase III is directly attributable to the composite action of the columns and spandrels.

The axial stresses in the columns are also reduced as a result of the additional concrete in the lower levels. From Phase II to Phase III the maximum axial stress at level 2 dropped from .819 ksi to .148 ksi. The drop in stress is due to the far larger cross-sectional area of the composite section. The large cross-sectional area, while creating an efficient lateral system, is also necessary for carrying axial loads. Concrete is ultimately not as strong as steel so the stresses in the composite sections must be less than the stresses in the all steel section in order for the system to be safe and efficient.

Phase 4

In Phase 4 concreting has progressed 45 stories, leaving 8 stories of exposed steel at the very top of the structure where the highest wind loads act. This leaves One Shell Square highly vulnerable to lateral deflections in the upper levels, where only temporary stay cables brace exposed steel. The maximum lateral deflection in this phase of 19 in. occurs at the roof level. The structure is at its full height of 691 ft in this phase. The criterion of L/360 provides a maximum deflection of 23 in. Under hurricane force winds, the exposed steel at the top of the structure will not exceed this deflection criterion.

The transition from composite sections to exposed steel framing occurs at the 45th floor. As a result, the axial stresses at this level are higher than at any other point in the model at 1.9 ksi, under wind load only (Table 1). This is still well below the ultimate strength of steel. Note that the maximum stresses that have been highlighted on the other levels are lower than this one. This indicates the effectiveness of the composite system.

Phase 5: Full Composite Structure

Phase 5 is not actually a construction phase —but a model of the completed structure. In this model, the

Table 1. Member force summary for phase IV under wind load

CONSTRUCTION PHASE	FLOOR	COL. LINE	FRAME	LOAD	P (Kip)	Area (in ^{2})	Axial Stress (ksi)	V_x (Kip)	M_z (Kip-ft)
PHASE IV	1	A	1	WIND	3269.32	5908.00	**0.553**	**310.31**	**4470.34**
	1	B	53	WIND	3.91	270.46	0.014	194.31	1776.36
	1	C	105	WIND	0.04	218.50	0.000	143.25	1294.02
	1	D	157	WIND	-4.24	270.46	-0.016	193.82	1772.35
	1	E	209	WIND	-3269.03	5908.00	-0.553	300.71	4424.38
	2	A	2	WIND	3106.55	5908.00	**0.526**	**287.35**	**3273.95**
	2	B	54	WIND	43.56	270.46	0.161	206.61	2463.70
	2	C	106	WIND	-0.11	218.50	-0.001	150.96	1794.71
	2	D	158	WIND	-43.10	270.46	-0.159	206.59	2463.13
	2	E	210	WIND	-3106.90	5908.00	-0.526	274.91	3237.89
	9	A	9	WIND	2318.69	5908.00	**0.392**	202.80	**1282.90**
	9	B	61	WIND	53.19	270.46	0.197	**215.60**	1404.66
	9	C	113	WIND	0.00	218.50	0.000	177.44	1153.08
	9	D	165	WIND	-53.21	270.46	-0.197	215.58	1404.53
	9	E	217	WIND	-2318.66	5908.00	-0.392	193.93	1263.75
	45	A	45	WIND	55.35	47.20	1.173	21.78	90.56
	45	B	97	WIND	65.75	35.00	**1.878**	30.79	229.45
	45	C	149	WIND	-0.04	32.70	-0.001	**34.50**	**242.61**
	45	D	201	WIND	-64.94	35.00	-1.855	30.44	227.05
	45	E	253	WIND	-55.93	47.20	-1.185	8.94	61.13
	52	A	52	WIND	-0.38	47.20	-0.008	**2.83**	**6.75**
	52	B	104	WIND	5.19	17.90	**0.290**	-0.22	-1.83
	52	C	156	WIND	-0.67	17.90	-0.037	0.62	4.26
	52	D	208	WIND	2.67	17.90	0.149	0.00	1.07

Table 2. Member force summary for phase V under wind load

CONSTRUCTION PHASE	FLOOR	COL. LINE	FRAME	LOAD	P (Kip)	Area (in ^{2})	Axial Stress (ksi)	V_x (Kip)	M_z (Kip-ft)
PHASE V (FULL COMP.)	1	A	1	WIND	3269.37	5908.00	**0.553**	**310.31**	**4470.34**
	1	B	53	WIND	3.79	270.46	0.014	194.31	1776.36
	1	C	105	WIND	0.04	218.50	0.000	143.25	1294.03
	1	D	157	WIND	-4.13	270.46	-0.015	193.82	1772.36
	1	E	209	WIND	-3269.07	5908.00	-0.553	300.71	4424.38
	2	A	2	WIND	3106.60	5908.00	0.526	287.34	3273.94
	2	B	54	WIND	43.44	270.46	0.161	206.61	2463.71
	2	C	106	WIND	-0.12	218.50	-0.001	150.96	1794.72
	2	D	158	WIND	-42.99	270.46	-0.159	206.59	2463.13
	2	E	210	WIND	-3106.94	5908.00	-0.526	274.91	3237.88
	9	A	9	WIND	2318.78	5908.00	0.392	202.79	1282.83
	9	B	61	WIND	52.99	270.46	0.196	215.60	1404.68
	9	C	113	WIND	-0.01	218.50	0.000	177.45	1153.16
	9	D	165	WIND	-53.03	270.46	-0.196	215.58	1404.56
	9	E	217	WIND	-2318.73	5908.00	-0.392	193.92	1263.69
	44	A	45	WIND	74.32	5908.00	0.013	85.18	444.08
	44	B	97	WIND	33.46	35.00	0.956	21.16	137.49
	44	C	149	WIND	0.09	32.70	0.003	22.71	147.97
	44	D	201	WIND	-33.33	35.00	-0.952	21.16	137.44
	44	E	253	WIND	-74.54	5908.00	-0.013	72.64	416.53
	52	A	52	WIND	-3.07	5908.00	-0.001	26.13	41.33
	52	B	104	WIND	12.75	17.90	0.713	1.88	18.03
	52	C	156	WIND	-0.19	17.90	-0.011	2.54	24.18
	52	D	208	WIND	11.67	17.90	0.652	1.99	18.14

exterior columns and spandrels have been completely encased in concrete for the entire structure. No exposed steel framing remains on the exterior of the structure and all of the perimeter elements act compositely.

Nearly the entire lateral load is carried in the stiff perimeter columns. This is the behavior that Fazlur Khan was seeking in this framed tube design. This is the most stable model, with the lowest element stresses and displacements at the top of the structure. The maximum displacements at level 45 have dropped 3 inches from Phase 4. This number also considers the fact that the composite structure projects a large area to the wind, resulting in a higher bending moment. The maximum moment at roof level in Phase 4 was 6.8 kip-ft (Table 1). The maximum moment at roof level in Phase 5 was 6 times larger at 41 kip-ft (Table 2). It will be observed that both values are of lower magnitude because the stiffness and cross-sectional area have both been increased significantly with the addition of concrete encasement.

Phase 5 shows clearly that the composite structural system is efficient under lateral loads. The success of One Shell Square as a structure in the New Orleans's windy environment emphasizes the effectiveness of the composite system.

Conclusion

The design innovations discussed in this thesis represent the works of the last century that allowed tall buildings to become skyscrapers without paying an exorbitant premium for height. The innovations represent the creative genius of engineers like Fazlur Khan, Myron Goldsmith, and Leslie Robertson who devised structural systems that had functional superiority and were financially competitive.

The structural tube form that all of these designers are masters of, provides lateral resistance through closely —spaced large columns and spandrels on the perimeter of the building. This creates a tube, which is stiff enough to resist bending in all directions.

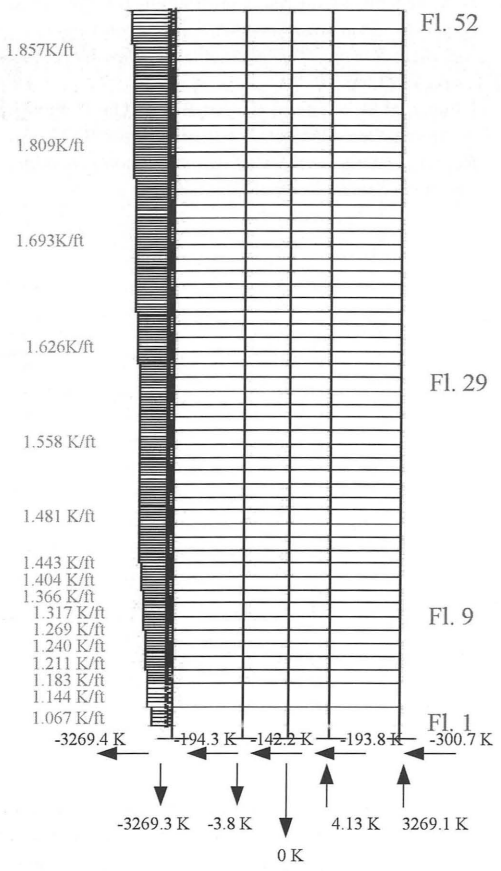


Figure 10
Construction phase 5 wind load analysis

Some framed-tube structures also have a core within the exterior tube to carry some portion of the lateral load or gravity load. The stiffness of any member is proportional to its moment of inertia and inversely proportional to its unbraced length. The framed tube gives short spans or unbraced lengths to the perimeter columns and spandrels, resulting in a high stiffness. The fact that the tube is on the perimeter of the building means that it is as far as possible from the centroid of the structure and has the highest moment of inertia. The Brunswick Building, World Trade Center, and Dewitt-Chestnut Apartments are early examples of framed-tube structures.

In the late 1960's another advancement was made when Fazlur Khan designed One Shell Square in New Orleans. The structure was to be the tallest framed-tube ever but it was also to be one of the first structures to directly benefit from the strengths of both steel and concrete. Steel would be used for its ease of erection and ability to span long distances in floor framing. A steel core was erected and a lightweight frame was assembled around it. Cable stays were used to position the steel and left in place for temporary wind support. The core carried all lateral loads during construction while sharing gravity loads with the perimeter columns.

After erection of 8 to 10 floors the perimeter columns and spandrels were encased in concrete. Concrete is a lighter material than steel so larger cross-sections can be used for sections before self-weight becomes a limiting factor. Concrete sections can therefore have larger moments of inertia than steel sections of the same weight. Placing these large sections far from the centroid of a structure serves to further increase their moment of inertia and their contribution to the stiffness of the structure as a whole.

The combination of these design innovations has allowed engineers to build structures more quickly that are taller and more cost effective. Composite construction not only fully utilizes the strengths of steel and concrete —it minimizes their weaknesses, while the framed-tube system provides higher stiffness than is possible in a traditional frame. These innovations have truly allowed us to overcome the premium for height. Study of such innovations allows us to see how they came into being, how individual engineers contributed to their success, and how the local construction constraints stimulated the search for such new ideas.

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On the daily amount of excavation for the construction of the rock-cut tomb during the New Kingdom Period of Ancient Egypt

Takaharu Endo

Introduction[1]

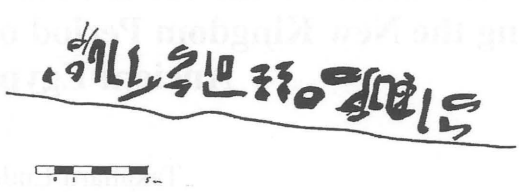
Rock-cut tombs are a well-known type of building from the early period of ancient Egypt. Their construction peaked during the New Kingdom period (*ca.* 1550–1069 BC). Many tombs of royal families and high officials were built on the western bank of a rocky mountain near the present city of Luxor. Many hieratic documents, written mainly by workers at the Kings' tombs in Deir el-Medina (Cerny 1930–35; Cerny and Sauneron 1935–70) inform us in detail about the organization of work in constructing these rock-cut tombs (Cerny 1973; Eyre 1987).[2] The daily amount of excavation by these workers, however, is not known because of the scarcity of any written records; thus, we have not succeeded in calculating the actual duration of construction from the size of the existing tombs.

Given this situation, we may now pay attention to the hieratic inscriptions left in Theban rock-cut tomb no. 32 (hereafter «TT32» in accordance with Egyptological convention). These inscriptions, recently described by Fábián from the Hungarian archaeological team (Fábián 1992), are mostly short notes containing measurements and dates. We can safely assume that the excavation workers left these graffiti to record their rate of progress. Unfortunately, as there seem to have been some errors in deciphering the dates in the hieratic inscriptions in Fábián's report, it cannot be used as a direct source for research. In this paper, I examine the amount of excavation per day for the construction of this rock-cut tomb, whilst reconsidering the decipherment of the hieratic inscriptions reported by Fábián.

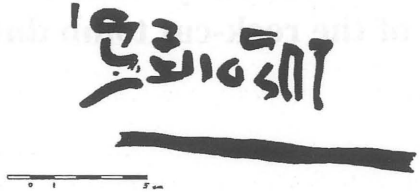
Reconsideration of the hieratic inscriptions left in TT32

The places where the hieratic inscriptions remain in TT32 are the ceiling and walls of the narrow corridor to the burial chamber, which stretches over 20 m in the same sectional form. The inscriptions often include a measurement and a date, accompanied by a horizontal line. The further into the rock-cut tomb, the later the date, and it is possible to calculate the amount of excavation per day by comparing the number of days between the recorded dates. In the ancient Egyptian calendar, a year was divided into three seasons: *Akhet* (inundation); *Peret* (emergence of crops, or winter); and *Shemu* (harvest, or summer). Each season was four months long, with each month comprising 30 days, and with 10 days in a week. By adding the five epagomenal days at the end of *Shemu*, a year totalled 365 days (Spalinger 2001). The dates written in the tomb are in accordance with this calendar system. The hieratic inscriptions and their interpretation are shown in Figure 1, and below is a reconsideration of the inscriptions that Fábián seems to have deciphered incorrectly.

[Inscription 5] Fábián interpreted the date of this inscription to be «day 29?», but according to the



1. extremity, the first month of *Peret*, day 6, inside measurement?
r-ᶜ 3bd 1 prt sw 6 q3b.f ḫbst (transliteration by Fábián)



2. the first month of *Peret*, day 23, extremity
3bd 1 prt sw 23 r-ᶜ (transliteration by Fábián)



3. the fourth month of *Peret*, day 2
3bd 4 prt sw 2 (transliteration by Fábián)



4. the first month of *Shemu*, day 28
3bd 1 šmw sw 28 (transliteration by Fábián)



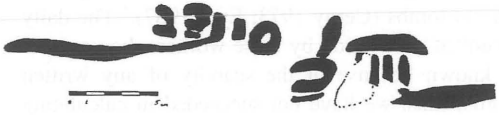
5. the third month of *Shemu*, day 29?
3bd 3 šmw sw 29? (transliteration by Fábián)
the third month of *Shemu*, day 15
3bd 3 šmw sw 15 (transliteration by author)



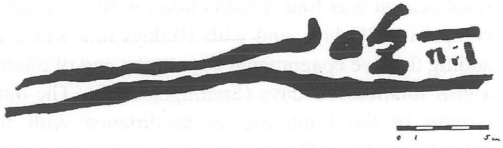
6. the second month of *Akhet*, day 23
3bd 2 3ḫt sw 23 (transliteration by Fábián)
the second month of *Akhet*, day 17
3bd 2 3ḫt sw 17 (transliteration by author)



7. the third month of *Akhet*, day 16
3bd 3 3ḫt sw 16 (transliteration by Fábián)



8. the fourth month of Akhet, day 25
3bd 4 3ḫt sw 25 (transliteration by Fábián)
the third month of Akhet, day 25
3bd 3 3ḫt sw 25 (transliteration by author)



9. the fourth month of *Akhet*, day 20+*x*?
3bd 4 3ḫt sw 20+x? (transliteration by Fábián)
the fourth month of *Akhet*, day 10
3bd 4 3ḫt sw 10 (transliteration by author)



10. ////// the fourth month of *Akhet*, day 26, 60 cubits
////// (3bd 4) 3ḫt sw 26 mḥ 60 (transliteration by Fábián)

Figure 1
Hieratic inscriptions with dates, inscribed in the corridor of TT32 (adapted from Fábián 1992, pp. 141–152)

palaeography in the New Kingdom period (Möller 1927, p. 60), it could represent «day 15».

[Inscription 6] As in the previous case, Fábián's interpretation of «day 23» seems to be incorrect; according to the palaeography it could represent «day 17».

[Inscription 8] Fábián translates this as «the fourth month of Inundation, day 25», but as earlier dates than this are inscribed further along the corridor, a different translation seems to be required. Additionally, a date from the inscription about 1.65 m further along from this inscription is translated as «the fourth month, day 26» (Figure 1–10). However, it seems impossible to excavate such a large section in a single day, considering the amount of excavation completed during other work periods. Although we cautiously acknowledge that it is possible to read the first hieratic in the figure as «the fourth month» as interpreted by Fábián, since the date is clearly interpreted as «day 25», it could also be interpreted as «the third month».

[Inscription 9] Fábián reads the date as «day 20 +x?», but according to the palaeography, it should probably be interpreted as «day 10». Because he translated the inscriptions in Figure 1–8, located before this inscription, as «the fourth month, day 25», he probably judged that all the dates on the inscriptions further along the corridor were later than «day 25».

Discussion

It is a well-known fact—for instance, from the ostracon discovered in the tomb of Senenmut (TT71), the high official who was in Queen Hatshepust's favour (Hayes [1942] 1973, pp. 21–23, pls. XIII–XVI)—that the amount of excavation was recorded after each day's work in order for the workers' supervisor to monitor the progress of the work. I believe that the short inscriptions found in TT32 are graffiti recording the progress of work, just as in the abovementioned hieratic inscription, although it is very rare to find an example of such inscriptions remaining in the actual architectural relics.[3] Moreover, in the case of TT32, the fact that it contains dates recorded intermittently for almost a whole year makes it a valuable source of information for studying the construction process (Figure 2).

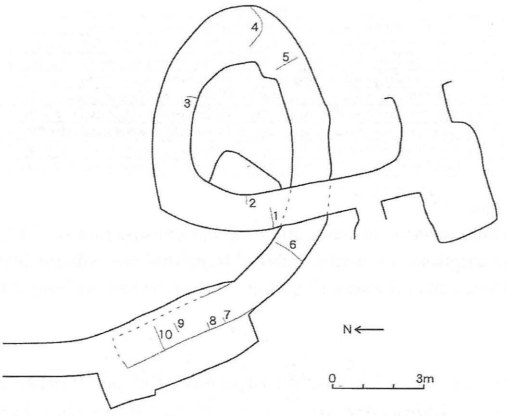


figure 2
The position of the hieratic inscriptions 1–10 in the corridor of TT32 (reproduced by author, based on Fábián 1992, Fig. 3)

In referring to the drawing of TT32 made by the Hungarian investigation team (Kákosy 1988, abb. 1), the section of the corridor where the inscriptions remain is about 1.58 m high and 1.05 m wide. Supposing the workers worked without any holidays,[4] it is possible to calculate the daily amount of excavation by multiplying the distance between the recorded dates by the cross-sectional area of the corridor (= approx. 1.58 m × 1.05 m), and then dividing it by the number of days between those dates. Based on the reconsideration of Fábián's translation in the preceding paragraph, the result of calculations using the abovementioned formula is indicated in Table 1. The amount of excavation was converted to *dny*, which was a unit commonly used in ancient Egypt (1 *dny* = 1 cubic cubit; 1 cubit = approx. 52.5 cm; 1 *dny* = 0.14 m^3). The number of days from «the third month of *Shemu*, day 15» to «the second month of *Akhet*, day 17» of work period V was calculated to be a total of 97 days, by adding five epagomenal days to the 45 days of the season of *Shemu* and the 47 days of the season of *Akhet*.

When we look at Table 1, some differences in the amount of excavation per day during each work period can be observed, but they tend to be approximately 0.5–1.0 *dny*. Concerning the number of workers engaged in the excavation work, one excavator with a few assistants behind him to carry out limestone chips would have been the best arrangement when we consider the limited workspace width of about 1.05 m. My provisional conclusion is

	work period	number of days	excavated distance	amount of excavation	daily amount of excavation
I	from "the first month of *Peret* , day 6" to "the first month of *Peret* , day 23"	17 days	1.24 cubits	7.43 *dny*	**0.44 *dny***
II	from "the first month of *Peret* , day 23" to "the fourth month of *Peret* , day 2"	69 days	10.76 cubits	64.57 *dny*	**0.94 *dny***
III	from "the fourth month of *Peret* , day 2" to "the first month of *Shemu* , day 28"	56 days	6.86* cubits	41.14 *dny*	**0.73 *dny***
IV	from "the first month of *Shemu* , day 28" to "the third month of *Shemu* , day 15"	47 days	3.24* cubits	19.43 *dny*	**0.41 *dny***
V	from "the third month of *Shemu* , day 15" to "the second month of *Akhet* , day 17"	97 days	11.62 cubits	69.72 *dny*	**0.72 *dny***
VI	from "the second month of *Akhet* , day 17" to "the third month of *Akhet* , day 16"	29 days	4.57* cubits	27.42 *dny*	**0.95 *dny***
VII	from "the third month of *Akhet* , day 16" to "the third month of *Akhet* , day 25"	10 days	1.33 cubits	8.00 *dny*	**0.80 *dny***
VIII	from "the third month of *Akhet* , day 25" to "the fourth month of *Akhet* , day 10"	15 days	1.90 cubits	11.43 *dny*	**0.76 *dny***
IX	from "the fourth month of *Akhet* , day 10" to "the fourth month of *Akhet* , day 26"	16 days	1.24 cubits	7.43 *dny*	**0.46 *dny***

Table 1
Daily amount of excavation for the construction of TT32. Each work period is based on the reconsideration of hieratic inscriptions, in section 2 above. Regarding the column labelled «excavated distance», the figures with asterisks are obtained from a plan (Fábián 1992, Fig. 3), and the rest are adapted from the description in Fábián's paper.

to set the daily amount of excavation per worker at 0.5–1.0 *dny* (0.07–0.14 m^3), and presuming that there were some holidays from work, this indicates that a volume somewhat larger than this was excavated in one day's work.

For comparison, we consider the hieratic documents of the New Kingdom period, which was contemporary with TT32. The study by Ventura (1988), who attempted to decipher papyrus number 1923 (stored in the Egyptian Museum of Turin), presumed that the scribe who had the role of controlling the work schedule for the excavation of the royal tomb of Ramesses VI made an estimate that «the project to complete the tomb in three years would go as planned if 108 *dny* were excavated per day (54 *dny* per crew with two crews working)[5] with 348 work days in each year». Unfortunately, as this papyrus has no description of the number of workers, the amount of excavation per worker is not clear. However, it is known from other hieratic documents that during the reign of Ramesses IV of the same 20th dynasty, between 60 and a maximum of 120 people—and during the reign of Ramesses IX, 62 workers in two crews composed of 31 workers per crew—were employed in the excavation of the royal tombs (Cerny 1973, pp. 103–108; Eyre 1980, p. 113). If we apply these numbers to the excavation of Ramesses VI's tomb, the daily amount of excavation per worker would be 0.9–1.8 *dny* (approx. 0.13–0.25 m^3), and this amount is not far from the abovementioned number for TT32. Therefore, although there is still scope for further investigation, we can safely conclude that a daily amount of excavation per worker of 0.5–1.0 *dny* is an appropriate gauge for calculating the number of days taken to construct the rock-cut tomb.

Summary

In this paper, I have examined the rock-cut tombs of ancient Egypt by focusing on the hieratic inscriptions on the ceiling of rock-cut tomb No.32 (TT32) in Thebes, which recorded the progress of excavation work. When I calculated the daily amount of excavation per worker during the construction of the rock-cut tomb, based on the reconsideration of the hieratic inscriptions first reported by Fábián, the result was approximately 0.5–1.0 *dny* (0.07–0.14 m^3). In addition, I have demonstrated that these values do not conflict greatly with hieratic documents related to the excavation of royal tombs in the same New Kingdom period as TT32. It is expected that this conclusion will shed new light on studies concerning the number of days taken to build rock-cut tombs in ancient Egypt.

Acknowledgements

Many thanks are due to Shin-ichi Nishimoto, Associate Professor of Waseda University, for reading through the draft of this paper and providing valuable suggestions.

Notes

1. This paper is a revised version of a paper written in Japanese by Endo and Nishimoto, 2002.
2. In addition, regarding practical methods for excavation of the rock-cut tombs, see Mackay 1921; Arnold 1991, 211–218; Owen and Kemp 1994.
3. Although it is not the case with rock-cut tombs, some successive hieratic dates with parallel red lines are

preserved on the walls and ceilings of the quarry at Qurna on the western bank at Luxor. This record is very valuable for quantifying the daily work on producing stone blocks at the quarry (Nishimoto, Kawasaki and Endo 2001; Nishimoto, Yoshimura and Kondo 2002).

4. According to the textual sources from the workers' village at Deir el-Medina during the Ramesside period, the days 9–10, 19–20, and 29–30 of the Egyptian month were generally regarded as holidays from work. However, if the completion of a tomb had to be hastened for some unexpected reason, then the excavation work was done with almost no holidays. Cf. Helck 1977, 145.
5. A number of hieratic inscriptions during the New Kingdom period indicate that the building crew was divided into two sides, called «*smḏy* (the left)» and «*wnmy* (the right)». However, it is difficult to determine whether the distinction was related to the actual work or to the administrative practice. Cf. Eyre 1987, 185–186.

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Shells and membranes in the architecture of the XVIIIth century

Félix Escrig
Víctor Compán
José Sánchez
Juan Pérez Valcárcel

The Baroque has been traditionally a style minimized by its tendency to the decoration and its lack of systematic. Gradually it has left demonstrating that this was a prejudice and that the architectural values were of first magnitude, comparable to the biggest landmarks of classic styles. As for the structural aspects we want to demonstrate that they overcome to as much as it was made previously by their space wealth, their economy of means and the intelligence of their solutions. Somehow they represent an antecedent of the shell architecture that so much it would make an exhibition with the Reinforced Concrete and the analytic techniques of dimensioning. With less means but with great intuition, the Baroque, invented forms of a complexity that today is still difficult to understand, at least geometrically. Paradoxically there are not investigations that help us to clarify the structural miracle of the Baroque since up to now it has been in historians' hands and not of architects or engineer's. This article tries to open road in this unexplored field.

Introduction

To speak of shell structures in the mathematical and modern sense of the term, in designs previous to 1900 and in materials different to the reinforced concrete it seems an excessive license.

However, since in the XIX century the brick vaults already demonstrated a good capacity to adopt capricious forms in absence of flexions and with the brick and the mortar like only materials. It is logical to think that the construction of this shells is previous to their analytic tools, so previous justification that it can be extrapolated to the Byzantine construction in that churches like Serlio and Bacchus or Sta. Sofía, they have been able to be designed like membranes, with great precision if we compare them with the results obtained by Finite Elements.

However the first properly shells are not found until the Baroque architecture, and not in fact in the Italian where architects like Brunelleschi, Miguel Ángel or Palladio did great achievements to overcome the structural challenges of the antiquity. It is later, when the economy of means that the XVIII Century imposed to the construction, when a great quantity of apprentices, that were formed in San Pedro's factory, were disseminated by Europe to create some national styles, rich in way, splendid of concept and good structurally.

The Baroque structures

The new generation that was in Italy, following Miguel Angelo and Borromini guidelines, preferred to materialize their structures in nerves and complex laces very of the medieval style. Guarini (Fig. 1a) or Vittone (Fig. 1b) they go in this line.

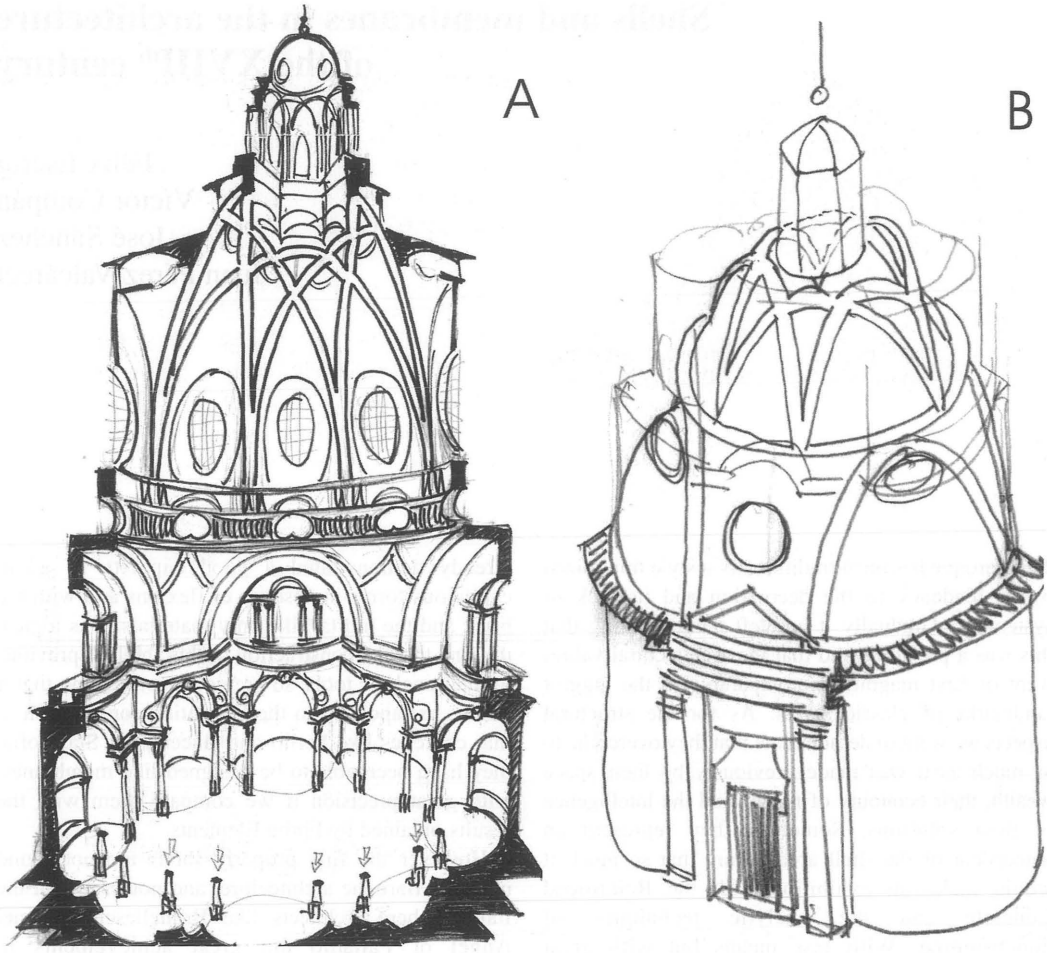


Figure 1a and 1b
St. Laurence in Turin by Guarino Guarini. - St. Bernardino in Chieri by Vittone

Who moved to the north they preferred to still use continuous forms more complex than the mentioned nerves, although masked under a dense ornamental layer of stuccos and paintings. Fischer von Erlach, patriarch of all them, in Austria, the family Dientzenhofer in Prague and Neuman in Germany are some few ones of among the dozens of architects that we could mention that, with its differences they dedicated to create suggestive and complex spaces with minimum structures.

While Fischer was devoted to explore the elliptic spaces (Fig. 2) and the Dientzenhofer family the intersected geometries (Fig. 3), Neuman manages with ease the most difficult spaces, mixture of ellipsoids and cylinders on punctual supports (Fig. 4a). Zimmerman gets geometries that don't have recognisable forms (Fig, 4b).

When we begun the study on the structures of the Baroque, we were surprised by the lack of bibliography and of specific studies. It is accentuated it in the case of the Central European Baroque, in the which, apart analysis made for consolidation works and repair or reconstruction, doesn't exist practically any research. We except Jager and Croci although they have not

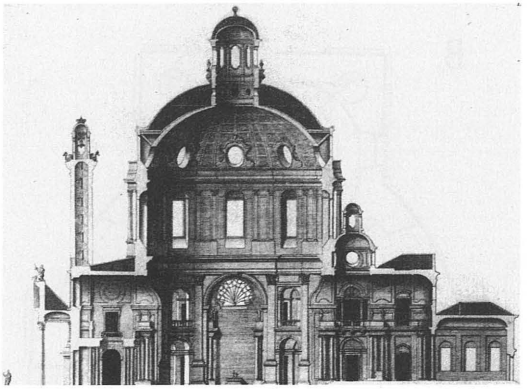


Figure 2
St. Charles in Vienna Fischer von Erlach

intervened in particular aspects of shells. It is for it that we contribute the data that continue with intention of to open the road and to demonstrate the great structural interest that has a recently valued style.

The work is wide and it will embrace the different types of Baroque membrane. But at this time it is logical to begin with important and very well-known monuments, like they can be:

1) Sanctuary of Kappel near Waldhsassen of George Dienzenhofer (Fig. 5a).
2) Church of pilgrimage of Steinhausen of Zimmerman (Fig. 5b).
3) Franciscan church of Verzhenheiling, by Neuman (Fig.6a).

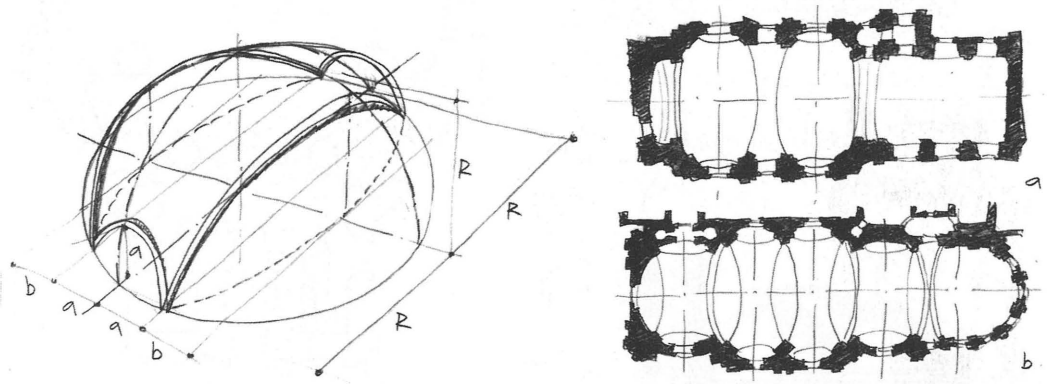
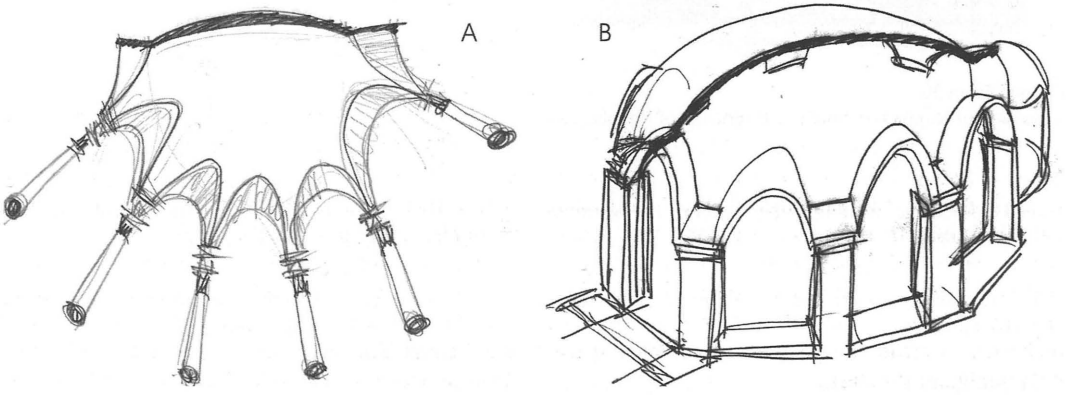
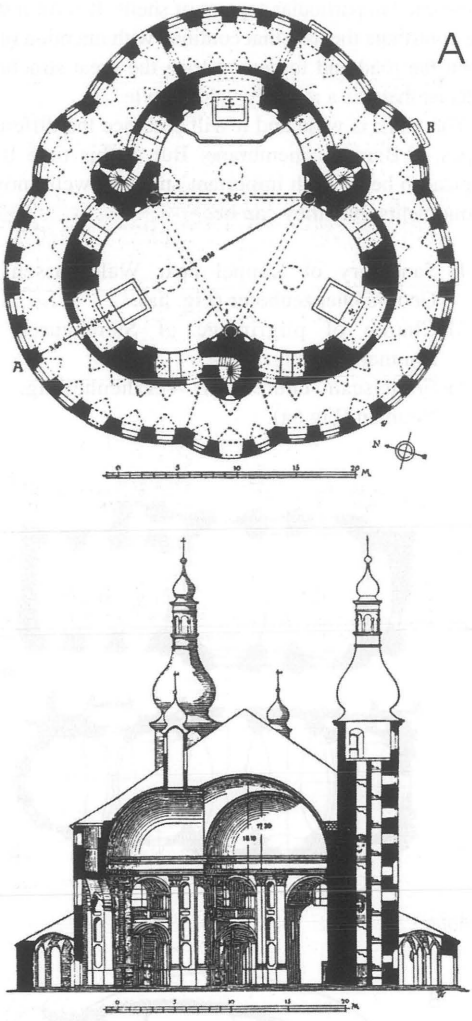
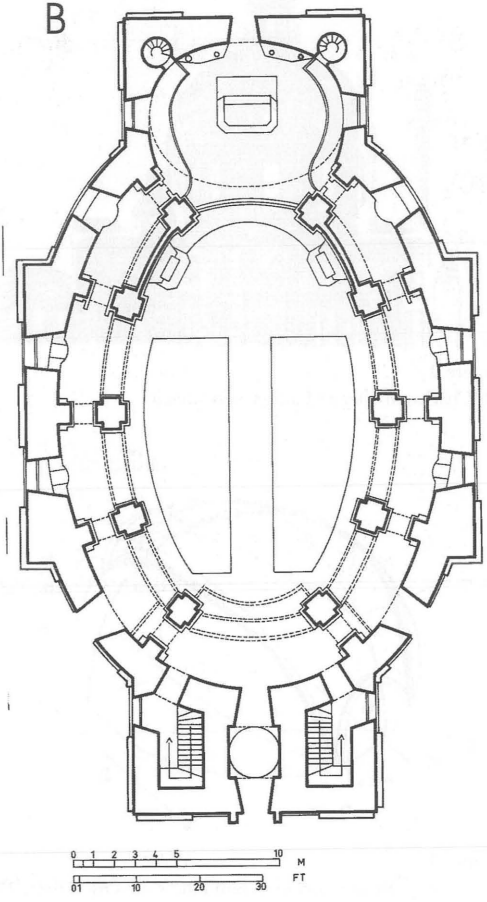


Figure 3
Selection parts of a sphere to build the vaults by George Dientzenhofer



Figures 4a and 4b
Type of Neuman Construction - Zimmerman's Steinhausen Church





Figures 5a an 5b
Sanctuary of Kappel. - Church of Pilgrinage of Steinhausen

4) Benedictine church of Neresheim, by Neuman (Fig. 6b).

In all these cases we will make the same suppositions:

a) For lack of data we consider that the vaults are built with bricks to thread and therefore with a thickness of 0.25 m.

b) The characteristics of the fabric are the following ones (Hydaka 1989):
   1. $\gamma = 1.7$ Ton/m^3
   2. $E = 10\ E^6$ Ton/m^2 and the material is elastic and lineal in the considered range.
   3. $\gamma = 1/6$

c) The vaults are supported by hinges on the cornices and only the part upon them are

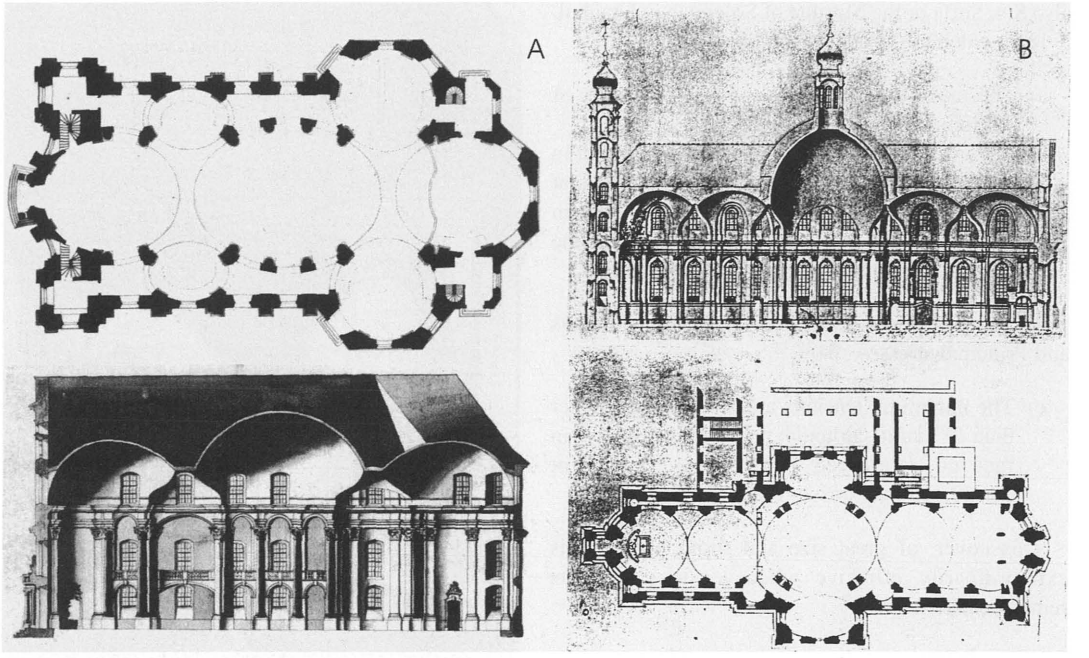


Figure 6a and 6b
Church of Vierzhenheiling. - Benedictine church of Neresheim

calculated starting from this level. It is necessary to keep in mind that the cornices, in the Baroque, define the form in plant and that what there are under them is well rested.

d) The only actions that we will consider they are those of own weight.
e) The mathematical pattern that we will use is to consider the medium surface of the vault as the geometry for analysis.
f) The method used to calculation is that of Finite Elements. The resulting graphics will represent the efforts and displacements in the considered surface.

Sanctuary of Kappel in Waldsassen. By George Dientzenhofer

In this case we have a estrange functional distribution with a triangular plan with curved sides, according to the geometric outline of the Fig. 7. It has odd number of sides, with solid walls perforated with chapels and stabilizing towers.

The dome is formed by a sphere that intersects with other three, and the group is supported in all its contour. There are not more perforations than some small chimneys that provide a soft clarity (Fig. 7).

George Dientzenhofer was able to solve in this small alpine chapel a temple of centralized plant that, in certain way, it was inspired by the Roman Panteon, with a certain form classicism but with the disturbing triangular form. Something that we will be for the first time in the Baroque and that gives certain keys of the style, it is the Ottoman reminiscence. In 1683 the Turks were about to take Vienna and, although they failed, this opened up a period of relationships diplomats with the Sublime Door, and, there were probably scientific exchanges and technicians. The hexagonal Ottoman plants gave cause to this triangular construction, as the Mosque of Serefeli and

also Sta. Sofía or the Mosque of Soleiman in Istanbul.

If we calculate in elastic condition we see:

a) The maximum deflections are, in this case, of 4.5 mm.
b) The maximum moments are of 0.32 Ton × m in a punctual case that is rested by the towers, that have not been considered in the calculation in the practice. In general, in significant areas the maximum moments are of 50% of this value.

The Fig. 8 shows deflections, Bending Moments and Principal stresses.

c) The maximum tensions are, in general, smaller than 13 ton/m^2, although, locally, in areas that in fact go reinforced and that we have not considered they arrive to 82 Ton/m^2.

This cover, of great size and form, misses it is extraordinarily effective whenever they stay its reinforcement nerves.



Figure 7
Interior of the Sanctuary of Kappel

Church of pilgrimage of Steinhausen. Nicholas Zimmerman

We are before a seemingly very simple form, of extraordinarily lengthened elliptic plant, because it

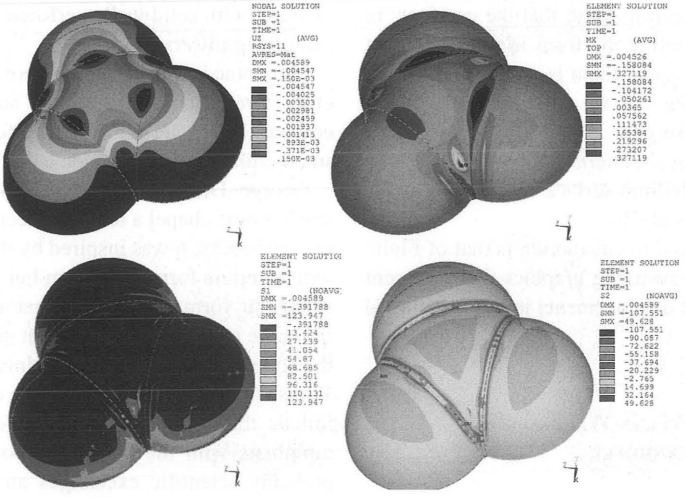


Figure 8
Deflections, Bending Moments and Principal Stresses obtained by the Finite Element Method

keeps a relationship from 5 to 3, what accentuates the directionality of an initially centralized plant (Fig. 5b). The dense ornamentation of the high part camouflages the form that becomes difficult to interpret in its simplicity. To it collaborates it the target of the supports that leaves seemingly suspended this cover. Here it is more difficult to find precedent, since the elliptic plants built so far are supported in all their contour. This and the little thickness of the vault, makes it an unbeatable novelty until Neuman enlarged the range of solutions.

The used geometric pattern is an ellipsoid upon ten supports (Fig. 5b). If we calculate in elastic state, we obtain the following conclusions:

a) The maximum deflections are of 0.226 mm. to own weight .
b) As for the maximum moments, except for due punctual areas to the grid of the mathematical pattern, the maxima are of 0.13 Tonxm. in the area among cylindrical openings or of 0.3 Tonxm. in the same perforations reinforcement. This is false in our case since they have areas specially reinforced by ornamental elements (Fig. 9).
c) As for the tension stresses, you leave in the Figs. 10 that the 9 Ton/m2 doesn't surpassed in any point.



Figure 9

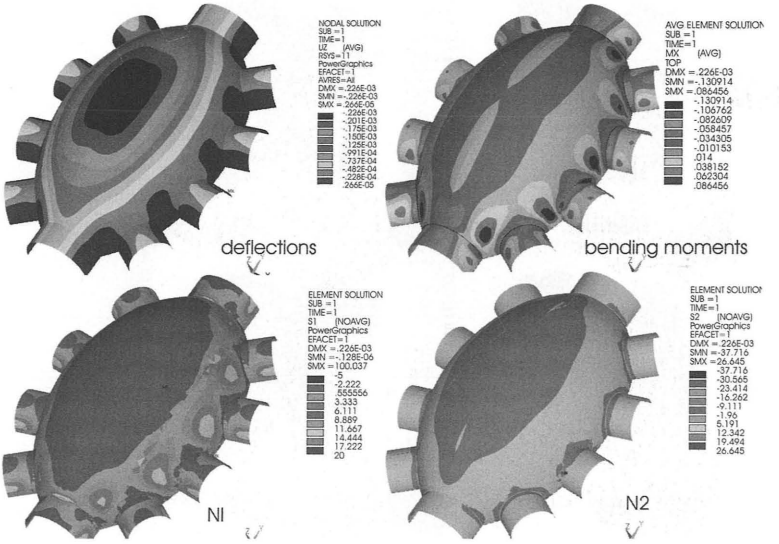


Figure 10
Deflections, Bending Moments and principal Stresses

On the whole it means it that it stops own weight and static loads give a safe state. This structure cannot have pathology and its design is good.

The Fig. 10 shows Deflections, Bending Moments and Principal Stresses obtained by the Finite Element Method.



Figure 11
Internal view of the shell

Franciscan Church of Vierzhenheiling. By Balthasar Neuman

Neuman was able to increase the complexity in the ways, even with more dimensions, by means of intersections of simple sheets fundamentally of type ellipsoid. We analyze two of their works although this is a to say in such a fruitful author that he made of each proposal a new investigation. In the case of Vierzhenheiling the chained convex spaces are looked for and they reveal the big geometry knowledge that had the contemporary architects, and the space domain that allowed them to it to have.

The geometry is extremely complex and the vault is formed by the intersection of three ellipsoids, two spheres, two cylinders and twenty-two cylindrical openings, in such a way that the whole group supports on twenty-four points (Fig. 6a). All the intersections

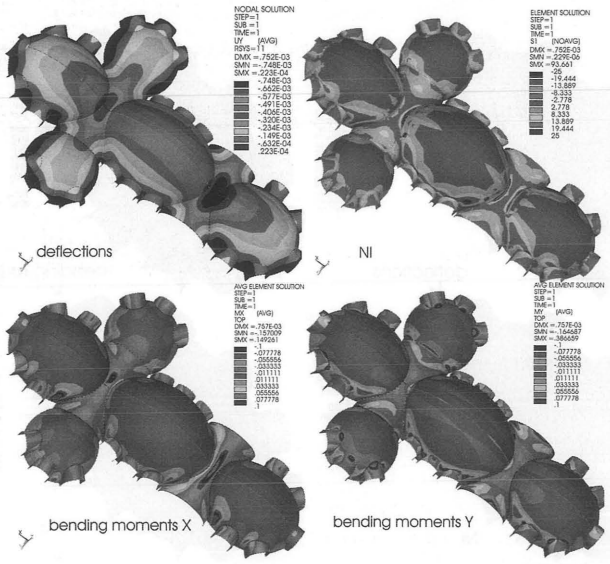


Figure 12
Deflections, Bending Moments and Principal Stresses ob tained by the Finite Element Method

and borders are considered finished off by nerves of 0.5×0.5 m. (Fig. 11). The analysis reveals behaviour as a shell with very good results that approaches to the membrane state, with the exception of some points.

a) In the Fig. 12 we appreciate the displacements that, in the worst in the cases, they don't overcome the 0.7 mm. in the key of the intersection cylinders.
b) As for the tension stresses we have a widespread state that it oscillates between 3 and –3 Ton/m^2. In the intersection nerves we even have 30 Ton/m^2 of traction stresses. For compression stresses, in the kidneys of the domes, it arrives to 30 Ton/m^2.
c) For the bending moments they oscillate among +/–0.15 Tonxm in the X direction. Something greatest are in the nerves in the Y direction. although inside the acceptable range.

Benedictine church of Neresheim. By Baltasar Neuman

The Church of Neresheim is still more complicated since, in spite of the symmetry appearance regarding the central dome, this is not such and the front part and the back one are different. On the other hand they are not cylindrical the agreement surfaces among each two domes but rather they are also ellipsoids.

The architecture of this church is extremely complex and it is one in the most complicated masterpiece in the whole Baroque (Fig.6b). Here we have the intersection of seven ellipsoids of different size and height with spherical canyons, in accordance with the geometry of the Fig. 13.

The structural behaviour of the group is deduced from the calculation by means of Finite Elements with the following results:

a) In the Fig. 14 are appreciated the displacements that, in the worst in the cases, they don't overcome the 16 mm. in the key of the intersection cylinders.
b) As for the tension stresses we have a widespread state that it oscillates between –9 and 3 Ton/m^2. In the pendentifs we even have 60 Ton/m^2 of traction stresses.
c) For the bending moments they oscillate among +/–0.20 Tonxm in the X direction. Something greatest are in the nerves in the Y direction although inside the acceptable range.

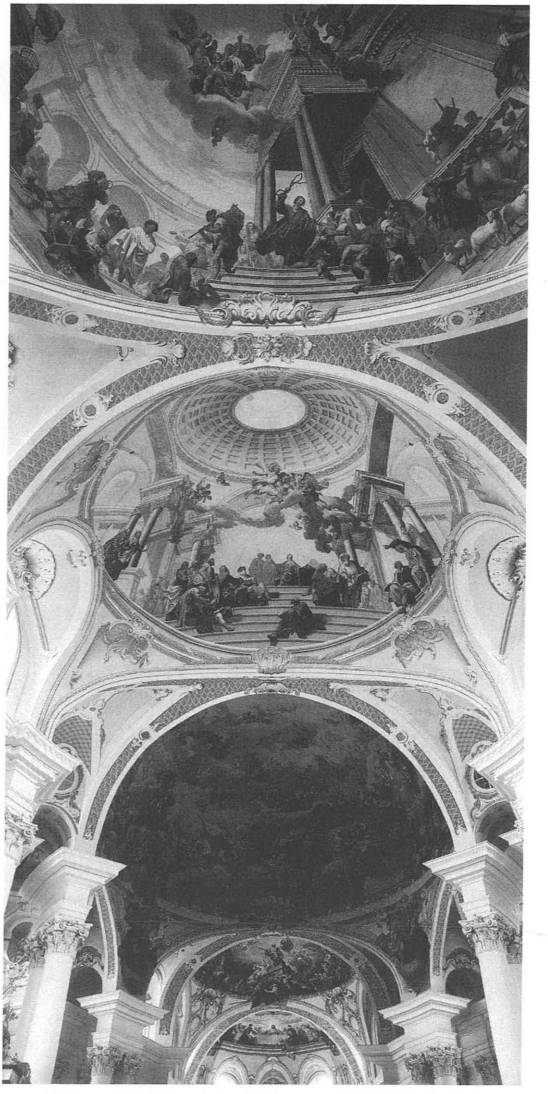


Figure 13
Internal view of the domes

Conclusions

Although it is difficult to establish some conclusions at the present state of the research we want point on

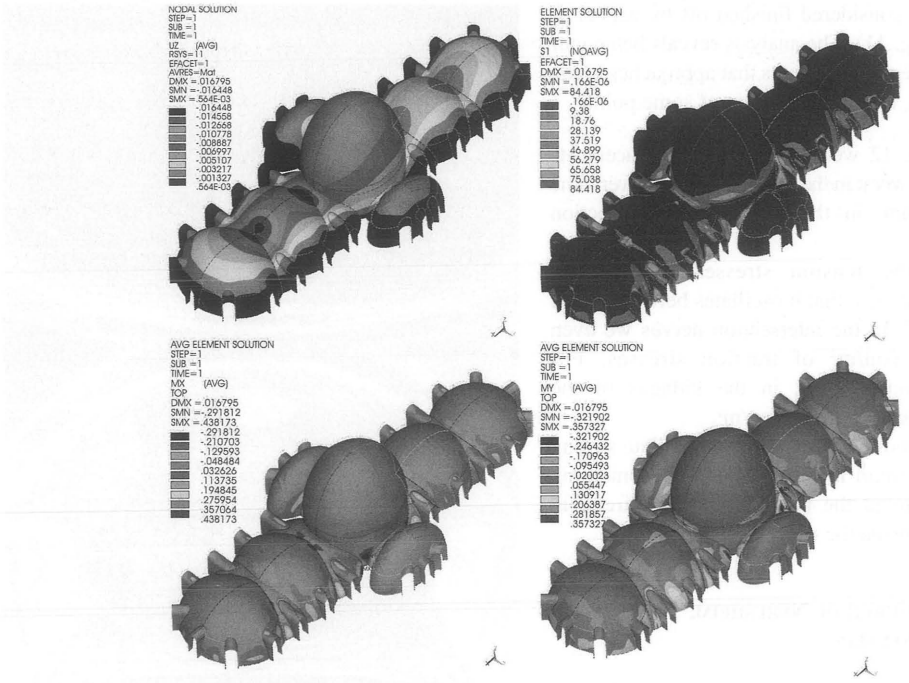


Figure 14
Deflections, Bending Moments and Principal Stresses obtained by the Finite Element Method

the interest of this kind of construction so little studied and so interesting. Our interest is to extend the study to all the Baroque proposals that are so differentiated of other styles, developed before or after.

A first approach allows to settle down some previous conclusions:

- The complexity of the layout is not a capricious artifice, since structurally they are of great effectiveness. Any other form would give bigger stresses and it would require other thickness.
- The behaviour like membrane is demonstrated and the flexions are not significant.
- We can say that they are the structures more complicated shells never built, and it will locate it, for own merit, the Centre European architects among the most important designers in structures of the whole History.
- The membrane state is accentuated in the borders in that some reinforcement nerves pick up the non balanced efforts.
- Another not explored chapter is that of the used constructive systems, since they are not geometries that admit layouts to line neither even wooden guidelines. They very probably never used complete scaffolding just as today in day we make with the armed concrete. When we can consent physically to the back of the vaults we will be able to advance some proposal.

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Contributions of André Paduart to the art of thin concrete shell vaulting

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Pierre Halleux
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The great era of thin concrete shells is probably nowadays over, at least in developed countries where the construction costs render this kind of structures uneconomic to build and where they appear obsolete from the point of view of the present day architectural tastes. It should nevertheless be pointed that this construction technique is an important legacy in the history of concrete construction and structures. It was an attempt to cover large spans with the most widely used construction material of the Twentieth Century and yielded structures that are now regarded as architectural masterpieces.[1] The design of thin concrete shells also fostered theoretical developments in structural analysis, in the mathematical theory of shells and in the theory of finite elements.

We may distinguish roughly two periods in the history of thin concrete shells: a period of precursors before the Second World War with eminent engineers such as Eugène Freyssinet (Fernandez Ordoñez 1979) in France and Eduardo Torroja (Torroja 1958) in Spain, and a period of blooming development after the war which ended abruptly in the 1970s, except for some kinds of industrial structures like cooling towers and offshore platforms.

In Belgium, the key figure in the design, construction and popularisation of concrete thin shells was certainly André Paduart (1914–1985). This paper endeavours to record all major thin concrete



Figure 1
André Paduart
(Photograph courtesy of SETESCO)

shells designed by André Paduart and to describe their originality in the context of the history of thin concrete shells.[2]

A short biography of André Paduart

André Paduart was born in Dover (G. B.) on November 4, 1914. He was educated in Ostend (Belgium) and graduated in civil engineering from the University of Brussels in 1936. After some months of employment with a naval construction yard at Hoboken (Belgium), he joined in 1937 the staff of engineers of SECO in Brussels, an office founded in 1934 by the insurance companies in order to enforce the technical control of the constructions. All plans of major and innovative structures in Belgium were and are still submitted to the approval of SECO before the beginning of their construction. For example, during the war years, Paduart was associated with the testing of the first prestressed concrete structure built in Belgium.[3]

He only became involved personally in structural design in 1944 when he joined as technical director the engineering company SETRA (Société d'Etudes et de Travaux), which was at the forefront in the application in Belgium of the new developments in concrete construction like prestressed concrete and thin concrete shells.

In 1946, Paduart presented a Ph.D. dissertation on the shear strength of reinforced concrete at the University of Brussels, and became in 1954 professor of civil engineering at his alma mater. He then left SETRA, but kept a private consulting practice, leading to the foundation of the structural engineering office SETESCO in 1957. At the head of this office up to his death in 1985, he designed or supervised the design of hundreds of buildings, bridges and other constructions.

From the mid-1950s to the mid-1960s, Paduart was a pioneering member of the Comité Européen du Béton (CEB) and of the Fédération Internationale de la Précontrainte (FIP), especially working in the committees on shear of these international associations.

André Paduart was also and particularly an active member of the International Association for Shells Structures (IASS) founded by E. Torroja in Madrid in 1959. He was a member of the Administrative Council of this body since its foundation and organized in Brussels in 1961 one of the very first symposia of this association (Paduart and Dutron 1962).

Shortly after, he published in French a remarkable small book covering essential theory, design and construction of thin concrete shells (Paduart 1961). The book was translated in English in 1966 (Paduart 1966) and a second French edition appeared in 1969 (Paduart 1969).

In 1965 Paduart received a special commission from the HAMON Company, which was and still is worldwide known for the design of cooling towers. The HAMON Company wanted Paduart to review the problems associated with the design and construction of large reinforced concrete hyperbolic cooling towers (Paduart 1968a, Paduart 1968b). Interestingly, it should be noted that this assignment occurred some time before the well known accident at Ferry Bridge (U. K.) on 1 November 1965 which saw the collapse in less than an hour of three large hyperbolic cooling towers under wind loading. With the support of the HAMON Company, Paduart gathered around him an international team of experts, which eventually became the Working Group 3 of IASS in 1970. Between 1970 and 1980, Paduart was the chairman of this WG3 and organized in Brussels two colloquiums on the subject (1971, 1975). The IASS WG3 issued its recommendations on the design of hyperbolic cooling towers in 1977 (Paduart 1979).

Meanwhile, in 1971, Paduart had been elected as 3rd president of IASS (after Torroja and Haas). He remained in that position until 1980. On the same year, he became honorary professor at the University of Brussels. In 1984, the IASS awarded him its prestigious Torroja medal.[4]

André Paduart passed away in Brussels on February 27, 1985.

Notable concrete shells designed by André Paduart

Cylindrical barrel vaults at Antwerp Harbour

Cylindrical barrel vaults have probably been the most used form of concrete shells. «The reconstruction after the devastations of the Second World War required forms of building which offered economy of material. This gave an enormous boost to the use of shell roofing in Britain as well as continental Europe,

since materials, particularly steel, were in short supply everywhere» (Morice and Tottenham 1996). The economy in construction, not the architectural value, was the key to the success and popularity of this kind of constructions. This explains certainly why the SETRA construction company was awarded the contract to build nearly 50000 square meters of warehouses at the docks of Antwerp harbour between 1947 and 1950 (Paduart 1950; Wets and Paduart 1954; Shell roof construction in Belgium 1952).

At the Albert dock, in front of quays 105, 107 and 109, SETRA built in 1948 a large shed 465m long by 60.6m in width. The shed consists of 31 bays, each covered with a self-supporting cylindrical shell spanning 15 m with a rise of 3 m (Figure 2). The thickness of the vaults varies between 8cm at the crown to 12 cm at the springing. Each vault is pierced with a large rectangular opening 40m by 3m to provide natural lightning. The bays were constructed one after the other by reusing the same centering and holding back the outward thrust with temporary ties. The rate of construction reached one bay per week. Particular features of this construction were the absence of permanent internal tie rods, the absence of edge beams, and the absence of any expansion joint along the entire length of 465m.

These sheds built at Antwerp by Paduart and Wets are the only concrete shells of that period in Belgium documented in detail and which were noticed abroad. They were the sole non- U.K. structures presented at the symposium on concrete shell roof construction held in London in 1952. Well-known U. K. specialist designers of the time underlined the originality of this construction in the discussion of the paper presented by Paduart (Wets and Paduart 1954, 222). Years later, the famous French engineer N. Esquillan still mentioned the centering used in Antwerp in 1948 as an interesting example of well conceived moveable formwork.[5]

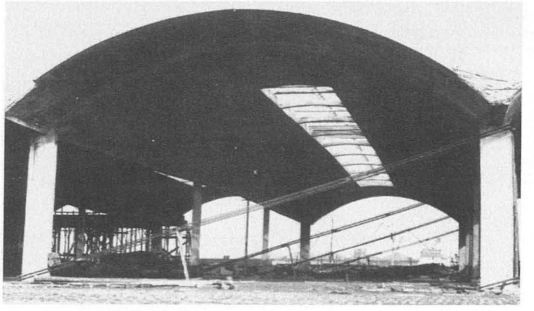


Figure 2
Sheds at Antwerp Harbour, 1948
(Paduart 1950, fig.11)

Two similar sheds, each measuring 255m by 47m and consisting each of 17 bays spanned by the same kind of shells were built by SETRA at the Leopold dock in 1950 (Paduart 1958). The centering that had been built for the construction of the sheds at the Albert dock was used again.

Airplane hangars

Thin concrete shells hangars had already been built during the First World War, notably by Freyssinet (Fernandez Ordoñez 1979) but a significant breakthrough was achieved with the construction of the two celebrated huge airship hangars built by Freyssinet at Orly in the early 1920s (Freyssinet 1923). On this occasion, the principle of the corrugated form for the concrete shell was introduced to obtain the necessary stiffness required to span 70m. Freyssinet also applied the same principle of corrugated shell roofing for the construction of two airplanes hangars spanning 55m at Villacoublay in 1924 (Gotteland 1925; Fernandez Ordoñez 1979).

In the late 1940s, free spans slightly exceeding 100m were achieved with thin concrete shells for roofing airplane hangars. The state-of-the-art led to radically different solutions in the U.S. and in Europe. In the U.S., the record span (103 m) was obtained with the two hangars designed by Roberts and Schaefer Company and built in 1948–49 at Limestone (Maine) and Rapid City (South Dakota). The free surface covered by each hangar is 10000 square meters. The form is basically a 13cm thick cylindrical shell stiffened at the extrados by external ribs (Allen 1950; Tedesko 1950). In France, the record span (101.5 m) was held by two hangars designed by Esquillan and built at Marignane (Esquillan 1952; Marrey 1992). The structure is much more delicate and appealing. Each hangar (101.5 m by 60 m) is covered by six arch shells 6cm thick with double curvature. Prestressed ties equilibrate the thrust of the arches. The hangars at Marignane were achieved in 1952, but they were basically designed in 1942 (Esquillan 1952).

In 1950, SETRA received the commission to build thirteen identical hangars on several military airfields in Belgium. Although the blueprints from 1950 mention Birguer as consulting engineer, the authors, who have known Paduart very well, believe that the driving force behind the design of these hangars was Paduart and Wets. Paduart mentions these structures with a rare discretion —perhaps because they were military constructions— in only one of his publications (Paduart 1958). The dimensions of these airplane hangars were 60 m (span) by 40m (depth). Each roof consisted of 6 corrugated shell arches 6cm thick spanning 60m with a rise of 5.73 m, the thrust of each arch being equilibrated by two high strength steel rods (Figure 3). There was no need here for the large record spans of the time, but the design bears certainly some similarity in principles with the hangars of Villacoublay (Gotteland 1925) and Marignane (Esquillan 1952). The hangars were built 1950–1952 at Chièvres (now a U.S. AFB), Beauvechain and Coxyde airfields, but most of them have now been removed or altered. They were certainly bold structures, maybe too bold, because it is known that one arch of a hangar under construction at Chièvres collapsed on June 6, 1951 a few time after decentering. The investigation yielded no explainable reason. On another part, measurements made in the early 1990s on several of the hangars at Chièvres revealed that the arches were significantly deformed.

The «Civil Engineering Arrow» at the Brussels 1958 international exhibition

The sheds at Antwerp and the airplane hangars designed by Paduart and Wets and built by SETRA were clearly engineer's structures with a strong utilitarian function. For all his later thin concrete shell

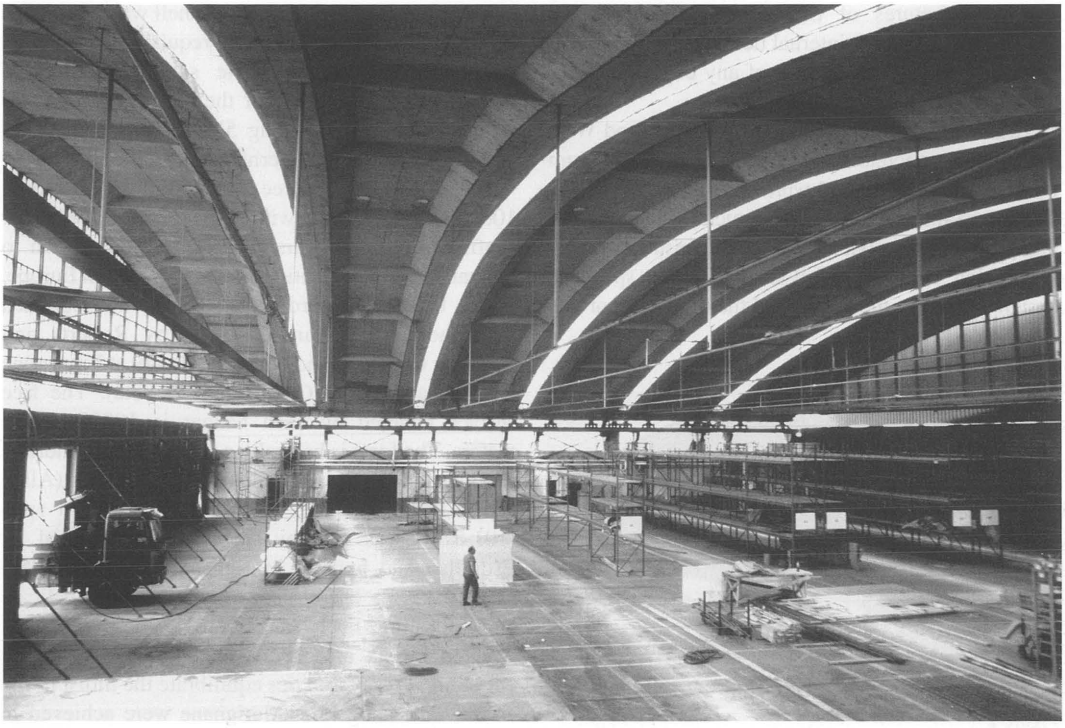
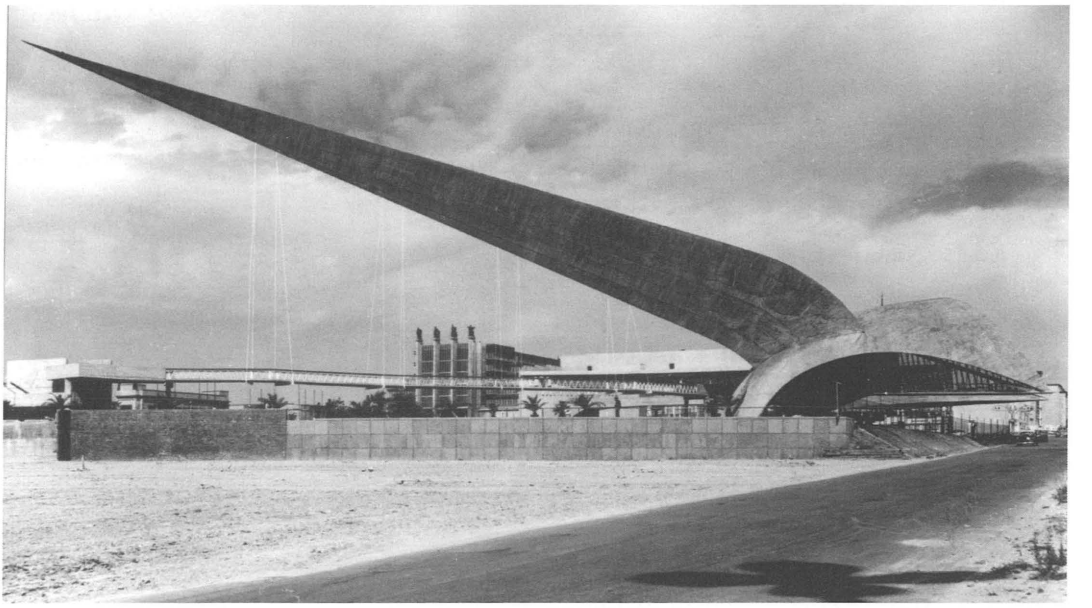


Figure 3
Airplane hangar at Chièvres, at the time of its dismantling in the 1990s



Fgure 4
The «Civil Engineering Arrow» at the Brussels international exhibition, 1958
(Photograph courtesy of SETESCO)

structures, Paduart would always collaborate with an architect.

For the 1958 Brussels international exhibition, Paduart and architect J. Van Doosselaere received an official commission from the Belgian government to design a structural symbol testifying of the «victory of [Belgian] civil engineering over nature» (Paduart and Van Doosselaere 1960). The structure (Figure 4) had to support a footbridge overhanging a 1/3500 map of Belgium where the civil engineering and public works were highlighted. The final structure, which was to be known as the «Civil Engineering Arrow», was a spectacular thin wall (4 cm thick at the tip!) reinforced concrete cantilever beam 80m long with an inverted A-section, balanced by a triangular shell roof with 29m-sides and a thickness of 6 cm (Figure 5). This concrete architectural structure gives a bold impression of equilibrium and «tour de force».[6] This construction, which made Paduart internationally known, has been described in detail by Paduart and Van Doosselaere (1958, 1960). The engineer and the architect jointly received the 1962 Construction Practice Award of the American Concrete Institute for their «Arrow».[7] The «Arrow» was dismantled in 1970.

Church in Harelbeke

The next involvement of Paduart with the design of a thin concrete shell structure was for a church in Harelbeke built in 1966 (Paduart 1968c). The architects were Léon Stynen, Paul de Meyer and André Vlieghe.[8] The structure looks like a truncated pyramid with an irregular hexagonal basis (Figure 6). The inclined bearing walls consist of thin corrugated concrete plane shells 6cm thick. The natural lightning flows from the inclined top through a grid that stiffens the rim of the truncated section.

Hypar shells

From the mid-1960s through the mid-1970s, Paduart was associated with the construction of several

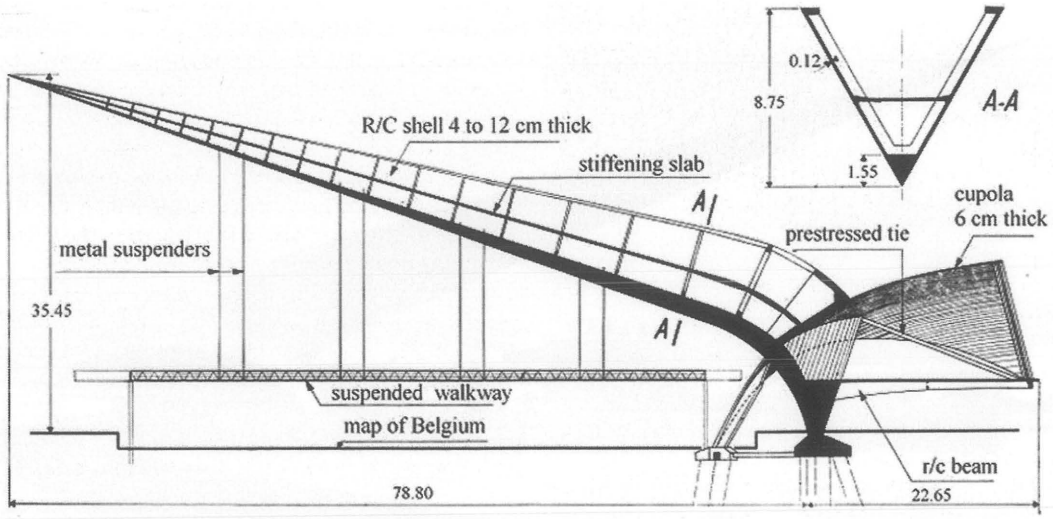


Figure 5
Longitudinal and transverse section of the «Arrow»
(Adapted from Paduart and Van Dooselaere 1960, fig. 5)

hyperbolic paraboloidal (HP) thin concrete shells. The use of such kind of structural form for shell roofing dates back to the experiments by Lafaille (1934, 1935) and the theoretical developments by Aimond (1933, 1936) in the 1930s. The success of this structural form rests for the architect in its appealing aspect, for the structural engineer in its simple structural analysis (under the oversimplifying assumptions of membrane behaviour!), and for the contractor in its economical formwork consisting in a system of straight planks supported by another system of straight lines.[9] This structural form has been especially popularised by the architect-engineer Felix Candela who built numerous hypar roofs in Mexico during the 1950s and 1960s (Faber 1963; Joedicke 1963; Billington 1983). We mention here only two hypar shells for which Paduart was the leading structural engineer, but several others designed by him or under his supervision still exist in the Brussels area.

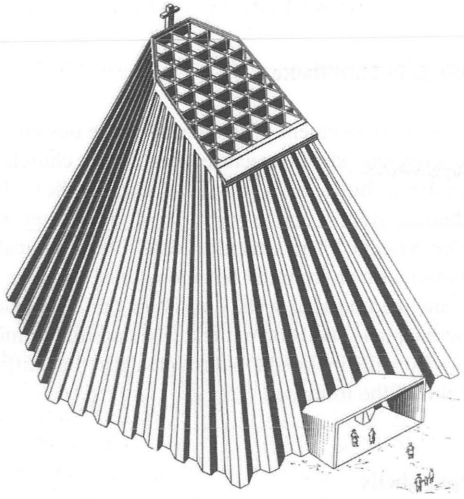


Figure 6
Perspective of Harelbeke church
(Paduart 1968c, fig.1)

The first of these hypar shells is a canopy in front of the Institute of Sociology at the University of Brussels (Figure 7). It was built in 1966 and the architect was R. Puttemans (Paduart 1967; Novgorodsky 1969; Paduart 1972). The canopy covers an area of 235 square meters and consists of an assemblage of four HP shells 7 cm thick resting on two inclined supports. The largest dimension of the cantilevered span is 12 m. Although much more pleasing visually, this structure bears some



Figure 7
Canopy of the Institute of Sociology at the University of Brussels
(Photograph courtesy of SETESCO)

resemblance in form and dimensions with the experimental shell built by Lafaille in Dreux in 1933 (Lafaille 1934, Lafaille 1935). Halleux (2000, 30) has suggested that this HP shell should be registered on a preservation list as the best example of thin concrete shells surviving in the Brussels area.

Much larger and original is the roof covering the swimming pool in Genk built in 1975 (Paduart and Schiffmann 1976, Paduart and Schiffmann 1977). The architects were I. Isgour and H. Montois. The form originated from a close collaboration with I. Isgour.[10] The structure is an assemblage of five HP shells covering a hexagonal area (Figure 8). The entire roof is principally supported on two abutments linked by a prestressed tie lying underground. The free distance between the abutments (longitudinal main axis) is 73.8 m. Transversally, the free overhanging is 36 m. The thickness of the shell is 7cm and not 5cm as reported by Paduart at the preliminary design stage (Paduart 1972). Concreting of the whole roof was done without interruption in one day. Visiting the worksite, Paduart saw on one occasion a heavy compressor left standing by the contractor on this delicate shell. This gave him the idea to study the influence of concentrated loads on the behaviour of HP shells, which are generally designed to carry distributed loading only (Paduart and Halleux 1977a, Paduart and Halleux 1977b).



Figure 8
Aerial view of the roof over the Genk swimming pool
(Photograph courtesy of SETESCO)

Grandstand of the Groenendael Hippodrome

The last involvement of Paduart with the design of a thin concrete shell was for the grandstand of the Groenendael hippodrome near Brussels in 1980 (Paduart, Schiffmann and Clantin 1985). The prototype of all grandstands of this kind is probably the structure designed by Torroja in 1935 for the Zarzuella racecourse near Madrid (Figure 9). But whereas Torroja used vaults having the shape of hyperboloidal sectors, Paduart and architects from CERAU designed here a folded plate roof (Figure 11). The length of the cantilever (13.5 m) is nearly the same at Madrid (Figure 10) and at Groenendael (Figure 12.) The total length of the Groenendael roof is about 106 m, without any expansion joint (remember the sheds and Antwerp!). The thickness varies from 7 to 12 cm.

Conclusion

Paduart was working at the edge between academia and engineering practice. Although he designed also bridges and buildings, Paduart will probably be best reminded for his contribution in the field of thin concrete shells in which he specialized. His realisations are not numerous but his production during thirty years at the heyday of this construction technique is eclectic with barrel vaults, corrugated shells, hypar shells and folded plates. He could teach the intricate mathematical theory of shells at the university, but used himself very simple methods derived from the Strength of Materials to design his



Figure 9
Grandstand of Madrid hippodrome, Zarzuella racecourse, 1935
(Photograph from Bull. IASS no.1, 1960)



Figure 11
Grandstand of Groenendael hippodrome, 1980
(Photograph courtesy of SETESCO)

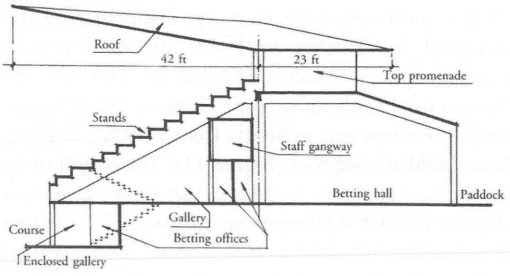


Figure 10
Cross-section of Madrid grandstand
(Torroja 1958, 3)

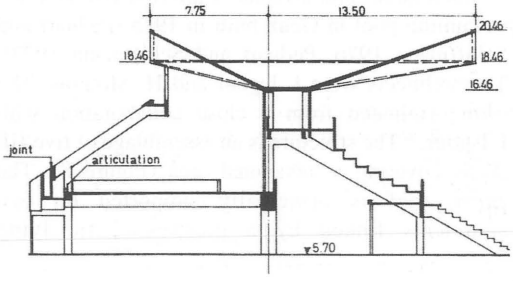


Figure 12
Cross-section of Groenendael grandstand
(Paduart, Schiffmann and Clantin 1985, fig.5)

own shells. This did not deter him from conceiving bold structures, at the limits of the utilization of the materials and construction techniques of his time, but he looked always forward with anxiety to the decentering of the shells, as testified by the careful records of the time-dependent evolution of deflection reported in many of his publications. He achieved international recognition by his pairs, not only for some of his own designs like the «Arrow», but also for the reliability of his personal involvement in international associations like the CEB and the IASS.

Endnotes

1. For an introduction to the history of thin concrete shells, especially in the pre-1960 period, see for instance Joedicke (1963), Billington (1983) and Melaragno (1991).
2. For an extended biography of André Paduart and the full list of his publications compiled by B. Espion, see Schiffmann et al. (2002).
3. An experimental railway bridge built (1943–1944) for the «Junction» between Brussels North and South Railway Stations, rue du Miroir.
4. Lopez Palanco, R. 1984. The Eduardo Torroja Medal awarded to Prof. Paduart. *Bulletin of the International*

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5. «Un exemple intéressant et bien conçu [d'échafaudage roulant] est celui relatif à une réalisation de 1948 en Belgique (Fig.11)». (Esquillan 1960).
6. «La flèche est contrebalancée par une coque; l'ensemble donne ainsi l'impression d'un tour de force (Fig.181)». (Michelis 1963, 157).
7. *Journal of the American Concrete Institute*, Newsletter, April 1962: 23–24, May 1962: 14–15.
8. Eglise Sainte Rita à Hareleke.1966. *Architecture* (Bruxelles) no.71–72: 386–387.
9. The surface of an HP shell is characterized by a negative Gaussian curvature, with two sets of straight or ruled lines.
10. Paduart, André, «Two examples of development of forms». Paper presented at the IASS Symposium Shells and Spatial Structures: the Development of Form, Morgantown, West Virginia, August 28–September 1, 1978.

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The formal unity of aerial vault's texture: The «trompes». The role of traditional «trait géométrique» for trompes' design in the perspective of the employ of modern CAD/CAM project/execution processes

Giuseppe Fallacara

This paper empathizes some theoretical/practical points connected to stereotomy, understood whether as a rigid rationalization of constructive method, or as an efficacious project/composition tool available for architects. This study follows the cooperated analysis of two works of Philibert de l'Orme; the 1st one, written 1536, is the juvenile one, the 2nd work is the one of the maturity written in the 1567.

The analysis has been made comparing the reasons of the classic stereotomy with the current cutting solids methods, pointing out conceptual continuity and affinity sure interesting for a researcher of the subject.

Study case. Lion: Philibert de L'Orme and les trompes de la Galerie de l'Hôtel Bullioud

The young architect's first work, just back from Italy

This case of study about the *galerie de l'hôtel Bullioud* 8 rue Juiverie built in Lyon in the 1536, is paradigmatic, considering stereotomy as the art of regulating.[1]

A gallery between two cabinets supported from a trompe, should regulate a small irregular medieval court. (Fig1)

If the gallery concept is not new and is proper of the tradition of Lyon, everything in the processing of this program is new.



Figure 1
Photo by the author (January 2002)

The Architect lets the power of his imagination go inside a rational universe.

> I've done this work in the 1536, as soon as I came back from Rome and form my Italian journey
>
> There I attended my architectural study. The two trompes have made for the general of Bretagne, Monsieur Billau, in Rue de la in Lyon (P.de l'Orme 1568 L IV, c II, f 90)

Only recently, starting in the 1964, with the Malaux low of the 1962, that the vieux Lyon is

classify as one of the first sector to safeguard in France. The Société d'Economie Mixte du Vieux Lyon starts projects for the restoring different buildings. The commune (municipalitè) establishes in the 1977 a program for popular house that includes the «hotel Bullioud». From the 1983 to the 1986 Jean Gabriel Mortamet, main architect of historical monuments, and Michel Allemand (HLM Society), restored the Philibert de l'Orme's gallery and 31 apartment houses more.(J.Salmon , J.L.Schefer 1989)

The trompes

> Most of you are asking, what I mean when I speak about a *trompe,* this term is used only from the insiders and so, because of that it is, just known from a few person, and from nobody of the now constructors. So I want to be clear with the Reader, I would like to warn him that, probably the word *trompe,* the one that we use here, better, we abuse, comes perhaps from the similar structure of a trumpet. Because both are large in the front and close in its self like a vault. (P.de l'Orme 1568 L IV, c I, f 89 v)

In these sentences, the author compares formally the musical instrument, the trumpet, to explain the geometry of the architectonical element, which at that time was known only by a few master masons.

> All vaults can be made as a trompe and all can be hang byair, without any support, except the two walls that create the angle; all this with a unique trait method. (P.de l'Orme 1568).[2]

A. F. Frézier in his book (A.-F. Frézier 1754), for the term *Trompe* he writes: « normally is a semi conic vault that shows us its base (he talks about the sectioned solid, with a plane passing through the vertex)». There are different kinds of tromps and their names comes from their functions or from their forms. For what concerns forms, there are conic and spherical trompes . . . When the face of one of this two is convex the trompe is called *en tur Ronde;* if the face is concavo we will have a Trompe en tour creuse; in case we will find an interrupted front because of level surface, the name is trompe à pan; if springers have different highs we'll have a rampant Trompe; if we have got an undulated face and more a rampant springer the name is Trompe d'Anet. Taking a look to the main configuration, in case we have a cantilevered Trompe, we call it Trompesur le coin, on the contrary, if curve inwards Trompe dans l'Angle. When we find the name Trompillon: that is the beginning of a Trompe, which is placed, in the spherical trompes, on a cone's vertex, in the conic Trompes and on a sphere's pole. It is only stone ashlars that take the space of most of all the conic vertexes. These vertexes otherwise could be as sharp, as not to be possible to cut, avoiding the risk of break.

Jean-Marie Pérouse de Montclos (J-M P. de Montclos 2001): in the chapter dedicated to the Trompes, remind that this kind of structure has been developed in European architecture in the 2nd part of the XV cent. It means that Philibert de l'Orme was not the first to use it *(trompe de l'hotel Pincé a Angers, or hotel Cluny in Paris).* But surely was him to create a theory about them. When (P.d l'Orme)he writes about, and when he creates the «trait» on the maison Buillion yard, he talks about the geometrical tracing that gives the possibility to . . . *on les peut faire toutes* . . . this is the reason for which le trompes are prototypes.

> Time ago, in Lyon, I project and I superintended works for two trompes, they were really big and complicated, because of the narrow space where they had to be

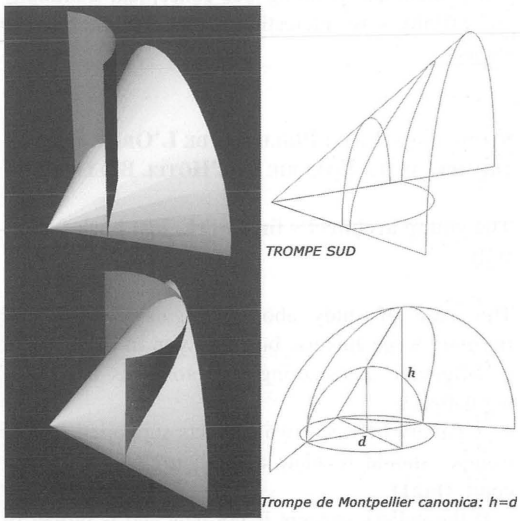


Figure 2
Drawing by the author (June 2002)

> construct; more, if one of these is rampant, sagged and curved on the front, the other on the opposite corner, is round on the front and of vast dimension. On both the trompes was erected some cabinets, connected by joining gallery from a trompe to the other: this all was hang by air, to give a possibility to connect one part of edify with the other, obtaining so cabinets for rooms. This job let this space became comfortable and strong; otherwise it would be uncomfortable, because of the that is too long and narrow. (P.de l'Orme 1568 L IV, c I, f 90)

The two trompes supporting the cabinets (the south one and the north one, on the left and on the right of who looks at those, by the front) are the tur Ronde kind. The south one is the already known from the freemason's corporations, de Montpellier (fig2), the north one is the one that has got more variants, Philippe Poité: (1536), notices that this is invention of the trompe of the Hotel Bollioud. Philbert gave a variant only for the curve, in the vertical plane, defining the cones generatrix. This in place of the semicircle will be described from a sagged and rampant arch.

The trompe de Montpellier, writes Jean-Marie Pérouse de Montclos (J.M. Pérouse de Monclos 2001, p125), is a famous variant of the trompe en tour-ronde. The archetype lain in *rue de l'Herberie in* Montpellier. The name comes out for the first time, without any comment, in Chereau.

Mathurin Jousse in his book) shows three variants of; *trompe en tour-ronde: trompe en tour-ronde*, avec fon Cintre (M. Jousse,1642 f 102–103, *trompe en tour-ronde, fous-biffée par Paneaux* (M. Jousse,1642 f 104–105*),* e *trompe en tour-ronde, autrement trompe de Mon-pellier* (M. Jousse,1642 f 108–109*),* —with relatives proportions.

About the firs kind he says:

> A trompe is called en Tour ronde, when on the vault is possible to built a cabinet, or something that could be assimilated at a round form.

About the third he write:

> This Trompe is called de Mon-pellier, because in the town of Mon-pellier exists a trompe like this, is beautiful and known among masons for its beauties and elegance.

Jean Baptiste De La Rue, *Traité de la coupe des pierres,* Imprimerie Royale, Paris 1728. trompe di Montpellier tav. XLV (there is nothing as difficult as get round the tops of ashlars, the one typical of la *tour ronde, I hope with this words a to explain it.)*, he explains properly how to proportionate the different parts.

This specimen is finalized to:

1) Rising the ideal/geometrical model or the mathematical one of the trompes in the galerie de l'hôtel Bullioud, voicing with different traits géométriques belonging to the trait method of the trompe d'Anet showed from P. de l'Orme.
2) Erection of the prototype of a *trompe,* lain on the south of the gallery of Lyon, this with the CAD/CAM process (virtual/real model) with the intention to use a quantitative/qualitative verifying program method.
3) Make the tension-computerized analysis of the geometrical model, verifying format compatibility of exchange data, making a quantitative/qualitative analysis of the architectonical element.

From the relief to the theoretical model: numerical model and mathematical model

Informatics models can be united in two families: the numerical models (points clouds of laser scanning, manual relief), and than the mathematical models (or theoretical) (R.Migliari 2002).[3]

«More: is necessary to start the relief's study with regular geometrical solids . . . » (C. Boito 1881 pp16, 22)[4]

The relief of the southern trompe of the gallery of the hôtel Bullioud 8 in rue Juiverie in Lyon, has been made following a particular methodology aimed to the retrieval of point in the space, these points were referable to the Cartesian coordinate through opportune triangulation. Tanking this method we obtain the numerical model of the intrados of the trompe, made by a discrete model «iron wire», that interpolates the different point relieved through a connection with a line segment.

This model moving from the idea to the realization, loses the original pureness of its planning conception, keeping constructive deformations.

One of the most common theoretical/practical points in architecture is the distance between the

designer engineer and the executants. This obliges to considerate all the variables during the realization . . . how match this distances reduces its self, as match will determinate the condition for the realization on the work (C. D'Amato 2002).[5]

The author do not describe the rule of the project, but the condition of the realized work, so this is first way to rise to the pure scheme of the project and its theory (geometric model or mathematical model), to get it realize.

The relief has been made on forms of the architectonical elements seen before, the trompe, has been compared to a semi conic vault.

Properly the stereotomic[6] element is comparable to a slantwise conic surface,[7] generated from a semi circumference direttrix (defined in a second moment of the relief), and from a segment line generator, this is the vertex of the element. All these lies in the perpendicular plane at semicircunference direttrix (that is the base). The conic area lain on the way in which the semicircunference direttrix extremes and the vertex line on the same horizontal plane. It means, for what we've written above, that the base is perpendicular to the aforesaid surface.

The monument intrados (the conic surface) shows the connecting joints of the ashlars of the trompe, which can be comparable to the generator segments of the conic surface.

The Cartesian area to find the points is made of:

- A horizontal plane passing from the vertex of its conic surface and the base's semicircunference extremes.
- A conic discretized surfaces (underlined from the ashlars contact joints).

As it is shown in the figure, the point A (characteristic for the intersection curve between conic surface and cylinder), in this method there is a double triangulation AVB, BVD, e/o AVB, BVC. (fig. 3)

The data table to find the numbers of the contour points of the trompe (intersection curve) is composed by 3 columns (to locate the point, the vertical triangulation, horizontal triangulation), and 17 lines (for the numbers of the ashlars of the trompe).

For a proper geometrical analysis (tomomorphologic) of the monument, the numerical coordinates, the one in the table, have been converted in a digital three-dimensional model, easy to analyze.

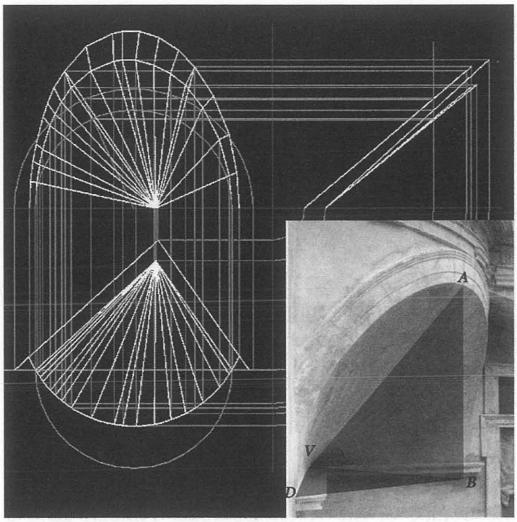


Figure 3
Drawing by the author (June 2002)

The Delormian method: trait geometrique of the trompe d'anet, codified in le premier tome de l'architecture

> On the trompe vault that I project and that I make erect in the Anet castle, to connect a cabinet to the room where took Hers journey, Her Majesty King Henry. *(P. de l'Orme 1568 L IV, c I, f 88 r)*

> And it seems to me a good idea to create an aerial vault, to find comfortably the place were to locate the cabinet. *(P. de l'Orme 1568)*

In the *trait géométrique* we find the geometrical model of the trompe, better, of all trompes, the same method already known from the hands of that age, and so is possible to combine in an infinitive way the three basic elements of the trait geometique: two horizontal sections, and a vertical section.

The novelty dwells in the attitude of de l'Orme, to figure out forms and architectonical characters in the pre- realization phase; now the attention moves on the project and on the control of it, match more than on the graphic strategy finalized on solving the practical problem.

In this tome we find the most charming treaties of

the 1522, about the creation of the trompe of the cabinet for King Henry in the castle of Anet (fig 4) (so we will not find the *trait géométrique* of the 1536).

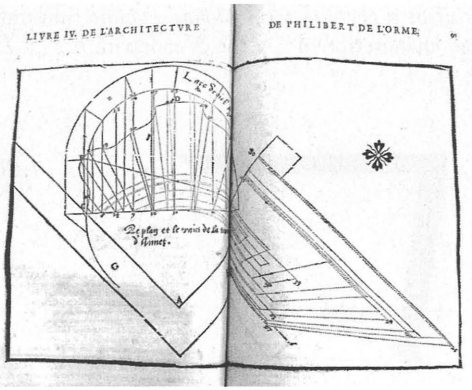


Figure 4
Drawing by the author (June 2002)

To rise now to the geometrical rule that preside the construction of *the trompe*, we've written about, we have to suppose to follow a deductive process for which the trait of Lyon trompe is structured as the back of the trait d'Anet, so: decrypting the geometrical model of the second one (existent the trait, inexistent do the monument), the numerical model of the first one could be interpreted in a proper way (inexistent the trait, exist the monument).

We finalized this compare to the analysis of these two models: The theoretical one and the physic one. The first one has got an opportune critic interpretation; the second one instead has got a right critic.

Analyzing the *trait géométrique* of le trompe d'Anet is possible to make an hypothesis about the method that Philibert de l'Orme proposed. With it de l'Orme hoped to decrypt the graphic. The intention was to have a punctual comprehension of the all parts that took part to the project/realization of the trompe.

We can finally find a triple kind of the trait:

- Project / composition kind
- Static /constructive kind
- Graphic /operative kind

The project / composition kind, is evident in the three sections[8] shown in the graphic. Changing these is possible to have infinitive[9] configurations of trompes (fig 5). The first section is the horizontal one, between the two walls, with a recto angle springer (not properly, because of walls deformations caused during the building) of the trompe. The second section is the horizontal of the building (*cabinet du roi),* which should be erected by the trompe, and particularly talking is a mix-line. He changes the way to draw, to design in that age. He employs his Italian culture. He changes the normal circular or squared plant typical of the age. The employing of these models is reserved to the sacred architecture; the trompe has on it the cabinet of Henry the II, sanctuary of his reflection (P.Potié, pp99–100).

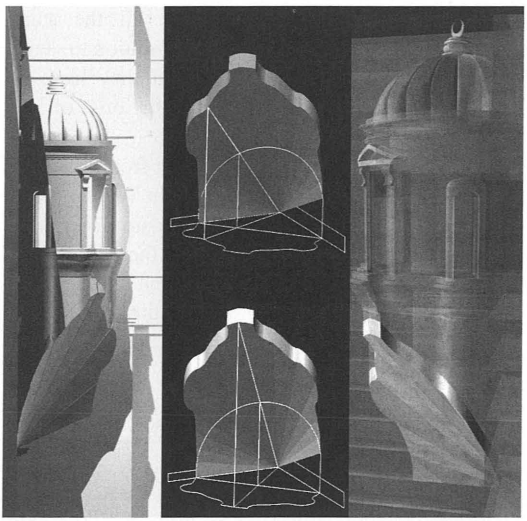


Figure 5
Drawing by the author (June 2002)

The third section is the vertical one (overturned on the horizontal plane), the one of the intrados of the conic vault, which could be compared to the direttrix curve of the conic surface. Correctly talking is an oval arch turned to vertical plane to become rampant.

As is easily possible to understand, the three section's interpolation, defining the monument d'Anet, are at the same time the exemplifications of the main method to construct a trompe.

The static /constructive kind is evident, in the structural section of the rampant arch. Here the structure is more stressed part and, is possible to notice the ashlars thickness, this sections corresponds to the larger structural span, beyond which level surface the vault is cantilevered. De l'Orme in this section draws the ashlars (7 for Anet), whit joints that probably were perpendicular to the tangent to the subdivisional points of the rampant arch. Is interesting to notice how to set the graphical elements of a trope, this section could[10] have made on all intermediate vertical levels, present between the vertex and our section, without giving any problems to the structure of the trompe. Statically the element increases its value, noting that this structural section has been built where there was the largest distance between the vault's supports. Verified the thickness hypothesis of the vault, is possible to verify all the static system. These proportions do not absolve all the static problems; we still can not have the condition to verify the cantilever of the trompe; in fact they have no empirical relation with the proportions of the elements.

The graphic /operative kind is clear from graphical traces of rotation and overturning of the line segments (that are the generators of the conic surfaces), with the aim to determinate the lengths of these.

Is possible to observe that the vertical section of the rampant arch[11] is essential to the erection of the center's trusses. These support the ashlars during the vault assembly.

To permit a good construction of the vault the wood trusses, need to follow the direttrix curve of the vault.

Now to have a unique *trompe of Lyon,* whit the Delormian method, «the three sections interpolation», we can rise to the only data not relievable on the monument. The vertical section of the intrados:

1) Horizontal section of walls springer: from the relief
2) Horizontal section of the *cabinet:* from the relief
3) Vertical section of the vault's intrados: indirectly drown

This last work has been made making sections from the discrete model that we obtain from the architectonical relief. This section almost correspond to a discretized semi circle, we suppose that in the ideal project this section would have be a semi circle.

All these data give us the possibility make hypothesis about the *traits géométriques* the two *trompes* of Lyon (fig 6) Is precious to note a similitude of the trait of the south *trompe* with the *trait* of a *pechina tore ridonda enbiaje,* illustrate in the manuscript of (A. de Vandelvira, *1575–1590.* f. 11 *v).*

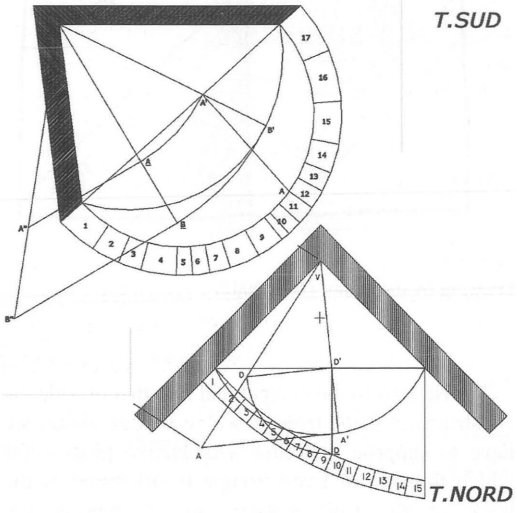


Figure 6
Drawing by the author (June 2002)

Now we continue with the graphical modeling of the trompes and with the error analysis between ideal model and the model of the work construct.

The overlying of these models show us how those two are really similar, underlining the coincidence between the theory of the project and the perfect execution of the stereotomic architecture.

Informatics modeling process and CAD/CAM prototypes and CNC* machine. Lyon; South Trompe

On the BF line you will do a rampant arch as it is possible to see from the figure, it has to be made of seven pieces, identified by numbers. In any case you could do the arch

of as many pieces as you would like, because as much will be the number of these pieces as resistant will the vault of the trompe and sweeter will be its line. (P.de l'Orme 1568 IV, III, 92r)

The method, that de l'Orme suggests, for the trompe erection needs for the aerial vault a discrete method of the intrados conic area. This condition is clear: «as much will be the number of these pieces and as much will the resistant at the same time will be the vault of the trompe and sweeter in its line». Tracing of the vertical section, the rampant arch, follows the involutional time for what concern the theoretical point of view: the moving from continuous to discrete. This section is sub-divided in a finite points numbers with the consequence the sweetness of the intrados area of the vault is proportional to the points quantity[12]. Even the static resistance enhances with the increasing of ashlars subdivisions. Is evident that in this way there is a better resistance of the ashlars with smaller dimension.

We can distinguish two different theoretical/-practical informatics elaboration: a discrete one and a continues one *(mesh e nurbs)* the first one is subdivided in triangular faces of the conic vault; the second one has no continuing solution on the vault surface. (fig 7).

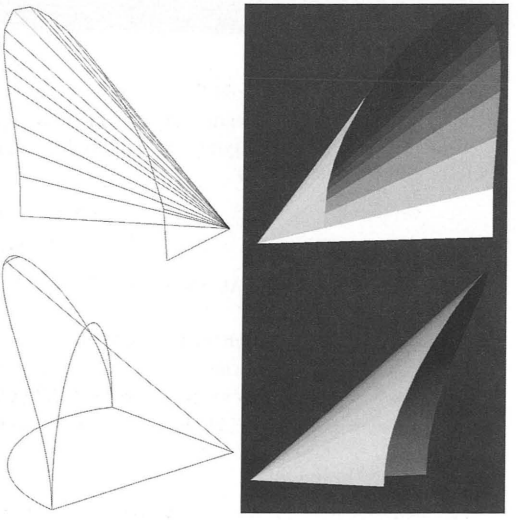


Figure 7
Drawing by the author (June 2002)

More: the first get approximate to the geometrical place of the second.

In the manual execution of the trompe ashlars, we follows the first method, but in informatics is easy to work with both methods, to see what the limits are at the discrete model, and how those limits are accepted by human eyes.

In any case the three-dimensional CAD can define the geometrical model that is on the base of the following actions.

To create the south trompe prototype with CAD/CAM techniques and with the CNC machine, we operate with the discrete modality according to the delormian method, with the aim to verify the esthetic quality.

We passed from discrete model of the intradossal/ extradosal conic surfaces to subdivide the trompe ashlars. (fig 8)

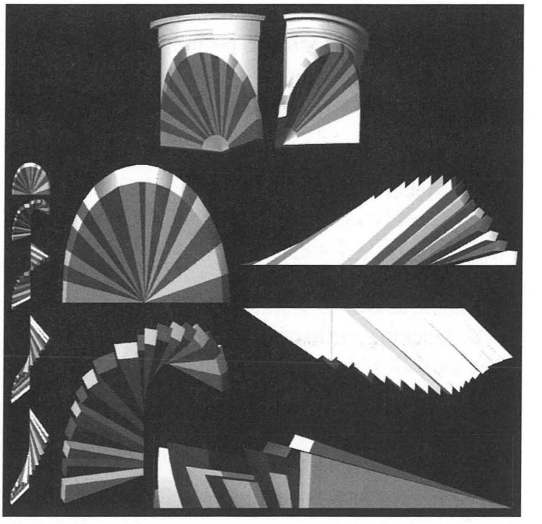


Figure 8
Drawing by the author (June 2002)

Working with different informatics modelers is possible to read, through the format (for ex: IGES = Initial Graphics Exchange Specification) the three-dimensional geometrical conformation and than going on.

As first; reshape and locate ashlars on the machine

The proportional reshape of the trompe has been

made considering the largest dimension connected to the working limits of the CNC machine: 5 axes EASY 11[13].

Considering this the best scale ratio results 1:4,7

It means that the prototype is five times littler of the original, having consequence on the material choice[14]; the prototype's scale has to follow the scale reduction to verify the esthetic and the quality of the work.

During the CAM project, we meet the first problem when we had to fix the row material on the machine. In this context an important role has the under-piece. The under-piece can have different conformations especially in the case in which the prototype element hasn't any support level surface. In this case is possible to analyze a trompe ashlar modeled whether with the discrete modality or the continuous one: conic Intradosal /extradosal surfaces with continuous modality, leveled areas with discrete modality, contact beds for leveled joints of both modalities.

It is evident that working with a continuous modality is more complex, especially conforming the under-piece as a conic surface (even a changing one) in the upper part of the support.

Working with discrete modality the Intradosal /extradosal surfaces of the vault reduces its self to level surface, positioned on a parallelepiped form under-piece. To optimize the process the under-piece was $76{,}75 \times 27 \times 5$ cm to let, all the 17 ashlars of the trompe) be anchorage (the dimension –the length- of these is $32{,}43 \text{ cm} < l < 60{,}86$).

The blocking method is given by an air pump; this is the most flexible method, in this way is possible to use rows of different size, with the only condition of a level surface.

Than we choose proper cutters,[15] for this program: the geometrical kind of the object, the processing method, the materials used, the velocity of the cutter rotation.

The processing method

1) Flattering of the 3 axes row piece to have the ashlar's thickness
2) 5 axes Processing for cylindrical surfaces of ashlar's top
3) Versor rotation for the ashlars contact bed processing, and for the bordering process with cylindrical cutter.

To find all parameter of the CAM we create a file postscript NC, readable from the machine controller 5 axes EASY 11, we used for processing.

Each ashlar has been processed at the velocity of 40' each; 25' to assemble it; 15' for shaving removing. (fig 9)

All the ashlars have been assembled in the *trait géométrique,* and than reported on forex support as horizontal springer of the vault aims to compose again the formal unity of the vaulted system. (fig 10)

In this way the trompe is analyzable under different points of view, geometrical / formal /static.

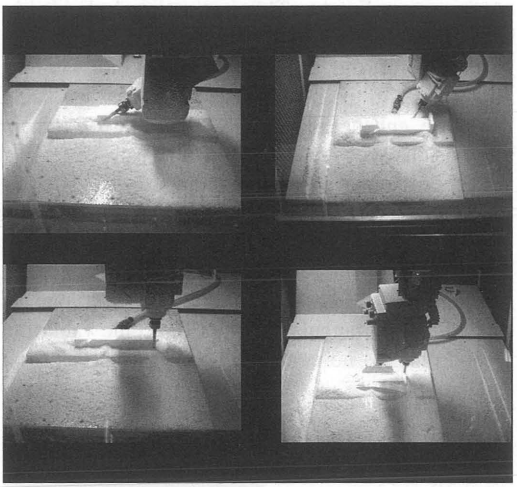


Figure 9
CNC Work phases for the prototype's realization of the Trompe (Laboratorio Cad-cam, Dipartimento ICAR, Scienze dell'Ingegneria Civile e dell'Architettura, Politecnico di Bari, June 2002)

Scale ratio and tensional analysis

> If these walls gave me enough trust, I would have build as long as the line AD was, instead ten or twelve feet, I would have done it twenty or twenty-four . . . So, on it I erect a cabinet, I am really proud if it nowadays is not possible to see cantilevered overhang that big. (P.de l'Orme 1568 IV, II, f 90–91)

Thanking these data is possible to rise to a real dimension of the trompe d'Anet, so is possible to

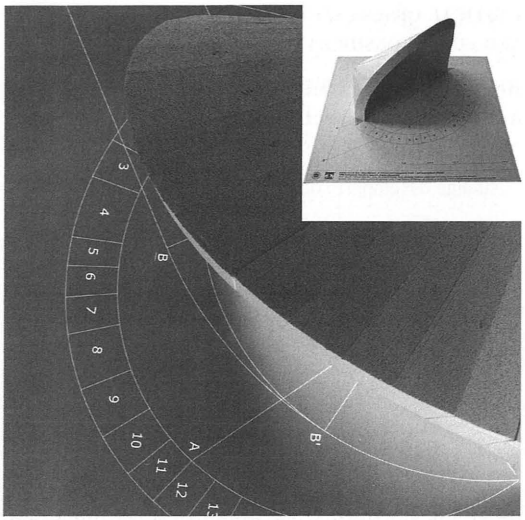


Figure 10
Prototypes of the Trompe (Laboratorio Cad-cam, Dipartimento ICAR, Scienze dell'Ingegneria Civile e dell'Architettura, Politecnico di Bari, June 2002)

make a physical compare with the south trompe of Lyon.

We now that: a French top=1,949 met. = 6 feet (16)

A French foot 0,3248 meter

The variation of the ashlar length (AD 10 – 12 feet) is 3,248 m < l < 3,90 m

Considering AD= 12 feet=3,90 m; is

	Trompe d'Anet intrados (we deduct from the treaties)	Trompe south Lyon Intrados (from relief)
Longest ashlar	3,90 m	2,94 m
Longest ashlar out of the wall sprinter	2,14 m	1,00 m
.max h from the wall sprinter	3,15 m	1,95 m

all the weight and the forces unload oneself on the corner, even tipping on, without collapse , if everything has been well done. (P.de l'Orme 1568 IV, II, 90r)

I notice that no one of the masons had heard about trompe like the one I project in Lyon, reduced, undulated rampant, with almost three quarter of the circumference overhangs. (P.de l'Orme 1568 IV, II, 91r)

Is necessary to observe that for what concern the trompe d'Anet the longest ashlar on the generatrix AD, has got more of the haft of is length out of the projection of the wall's springer. (Fig 11)

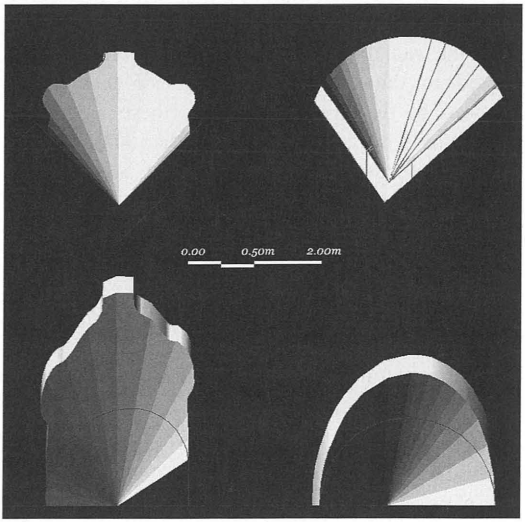


Figure 11
Drawing by the author (June 2002)

With opportune vectorial data conversion techniques is possible to read the geometry of the Lyon trompe and so apply a tensional analysis.[16]

The trompe model has been analyzed, with the aim to individualize the global static of the monument, having the help of the analysis software.

We did an accurate static analysis of the three-dimensional structure. We used as first the discrete method for shell quadrangular elements, with linear elastic behavior. This kind of behavior for stone elements is justify by a low tensional state of those.

The theoretical base of this software is based on matrix analysis of the structures, using bi-dimensional elements «shell kind» under superficial force actions, coming from perfect joint of elements.

To better understand the elastic characteristic of elements, we took as reference stones with coefficient of elasticity E = 200.000 Kg/cm^2, weight P 2800 Kg/m^3.

The model has been developed on a bound hypothesis of a perfect joint on the terminal section of the vault. The statically analysis, done automatically, determinates the calculus and the assemblage of the rigidity matrix of every elements on the memory available on the computer.

From the tensional diagrams is possible to observe two different effects:

In the radial direction the normal tensions are related to the overhanging behavior that brings tractions to the trompe extrados (these are at the maximum in the central areal near the joint),

In the direction of the circumference is evident the oblique inflexed effect. The system give the possibility to unload some of the load, that otherwise would remain only in the radial direction, increasing the traction solicitation. In this way is created an arch effect that moves the load on the extern part of the vertical supports. In the case in which there is a load concentrated on a extern side of a trompe, these benefit reduce (fig. 12)

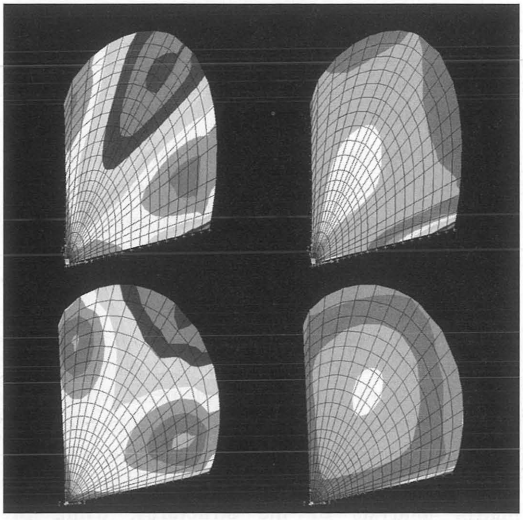


Figure 12
Drawing by the author (June 2002)

Critical observations and final considerations

Biuniqueness relation between trait geometrique method and prospective representation

> Is possible to think how the kind of the trait can have a so strange develop. (P. de l'Orme *1568 IV, I, 88 v)*

> I wanted to make it more difficult and with a strange form to let it have nicer a form to see. (P.de l'Orme *1568 IV, II, 89 v)*

The prospective representation (P. de l'Orme *1568 IV, II, 89 r)* of the cabinet du roi illustrated by Philibert de l'Orme give as the possibility to make some consideration on the relation between the *trait géométrique* (P.de l'Orme *1568 IV, II, 92–93)* and the architectonical composition of the monument. First of all he thinks or not if the bi-dimensional rule of the trait is on the base of the project of the monument of vice versa if this is just a consequence of a rationalization of the control rules during the executive phases of the work.

Considering that the draw illustrated in the treatise is successive to the cabinets realization, is possible to think on some hypothesis:

1) The representation, refers to a draw of the cabinet, in which the formal intentions of the designer engineer are evident, and this before the editing of the *trait géométrique*
2) The prospective representation was made on the site, when the work was complete, so it describe the monument in all his parts, from the theoretical/constructive elaboration of the *trait géométrique*
3) The prospective representation has been made from an engraver, that didn't now the *trait géométrique* and finalized his draw to a representation the work for the treatise

In the first hypothesis the *trait géométrique* would follow the spatial disposition of the designer engineer, being so the rational means of the executive control of the work.

In the second hypothesis, it should admit that, even if the prospective representation is perfect, there is not correspondence between *trait géométrique* and reality. This hypothesis contrasts the one of de l'Orme but agrees with this paper.

The third hypothesis there is no intention to finalize the grfic method of *trait géométrique* to the project/ creation of architectural stereotomic form, the homological passage would have be evident between the *trait* and the prospective representation; and it dosen't happen.(T. Maldonado 1998 p. 101)

Reminding what Camillo Trevisan wrote, that in the f. 106v of his treatise de l'Orme complains about the modest quality of the draws, giving the guilt to the engravers.

J. M. Perouse de Montclos: «le graveur dont de l'Orme se plaint, n'a pas su représenter l'ouvrage».

Philippe Potié underline that the delormian project hypothesis has got an anticipation rule on d'èpure, comparing it to the spatial project. (P. Poiré, insc.101) The form of the projected object is the consequence of choices made on the èpure constructive tracing.

Now the pre-figurative intuition of a spatial curve, as the result of intersections of surfaces and different solids is difficult: the method assures a rational answer about the execution/realization of the work, but not on the aesthetic control of the form; because is not possible to have a three-dimensional vision of the work but only the bi-dimensional one.[18] Is not difficult to believe the figurative capacity, of spatial curves, increase proportionally using the *trait géométrique* method, in this way is possible to get under control forms in the spaces, at the same time using parametrical/ variational modeling techniques effects are amplified.

The analogy between the delormian method and the solid parametric modeling techniques, based on feature[19], applied on stereothomic elements, assure the novelty and the continuity of results. (fig 13)

The deep synergy between techniques, processing and theoretical /applied instruments, leads us to think about the way to project and to analyze a planned work.

This is my contribute[20].

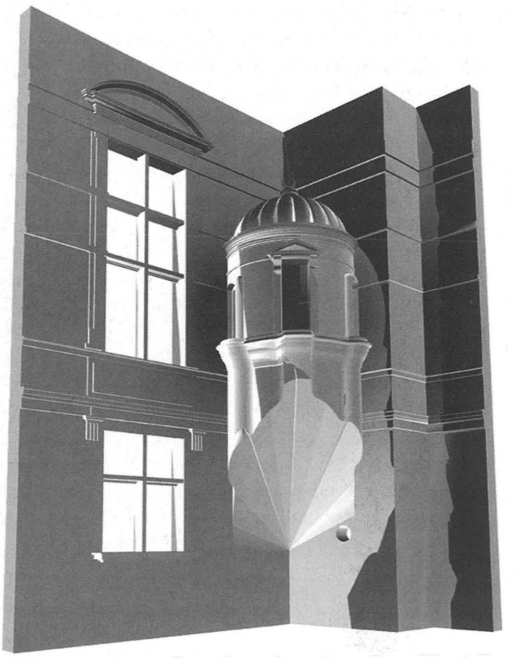


Figure 13
Drawing by the author (June 2002)

Notes

1. Regulating: or accomodare, from latin *commodus: adapt.*
2. For what concerns la cupe de pierres, and generally all draws that define a vault, could they be on plant, prospect, section or developed. This term has a largest meaning than épure, because we mean the draw whether on a natural scale (1: 1),or with reductions. Normally the épure is only on natural scale. A.F.Frezier 1754
3. Riccardo Migliari: geometrical models, For a relief and rappresentation theory. Giornata di studi sull'architettura in pietra da taglio. *Architettura e stereotomia: tradizione e innovazione.* 3–4 giugno 2002, Bari. Politecnico di Bari Dip.'I C.A R «La Sapienza» Dip. di R R.
4. Camillo Boito, *Ornamentidi tutti gli stili.* Ulrico Hoepli, Milano, 1881. pp. 16,22.
5. Claudio D'Amato, *CAD/CAM Planning modesl.* Study day on in cutting stone architecture. *Architettura e stereotomia: tradizione e innovazione.* 3–4 giugno 2002, Bari. Politecnico di Bari Dip.'I C.A R «La Sapienza» Dip. di R R.
6. The geometrical conformation of the trompe is given from the intersection of a particular recto cylinder and from a particular slantwise cone.
7. References to the «trompe réglée» the fluted trompe A. ch. D'Aviler, *Dictionnaire*, article *trompe*
8. Two horizontal levels lying on a surfaces and a vertical overturned on the horizontal level.
9. Infinitive anthill three, for how many parameter there are in the function/ trait
10. D. Aita, Dip. I.S. Università di Pisa, *Una possibile*

rilettura del problema dell'arco tra geometria e meccanica, XV Congresso AIMETA di Meccanica Teorica e Applicata

11. Is possible to individualize 5 graphic methods for drawing a rampant arch, to have harmonic proportion between parts. *Tratado pràctico de Estereotomia, aplicaciones al corte de piedras, maderas y hierros. Por Francisco Ponte y Blanco, La Coruna, 1921*
12. CAD = Computer Aided Design, CAM = Computer Aided Manufactoring, CNC = computerized numerical control
13. EASY 11 (E = Opened structure, moving desk 30° inclined, 1 = single desk, 1 = processing unity. Different kind of movements, m. longitudinal (axes X), m. transversal (axesY), m. vertical (axes Z). *Length of axes*: X = 1000mm; Y = 1200mm; Z = 650mm; C450°; B = +/– 160°; max velocity 24000 gir/min.
14. To construct the Lyon gallery Philibert chooses a local stone, Oolitic limestone, better known as the lucenay stone. The caves situated near Lyon had always been used for elegant building construction. The material used for the prototype is polystyrene, with a density of 30 Kg/cm.
15. Tools kinds:1) cutter for forms;2)c.cilindric;3) c.spheric. Normally cutters are used at the end of a work and working on borer an on engraves
16. My regard goes to the eng. Giuseppina Uva reserecher at the Politecnico di Bari Facoltà d'Architettura, and to the eng. Girolamo Fallacara expert in geometrical modeling finalized to the structural calculation.
17. French foot = 0,3248 m, Vineies foot = 0,3161 m, Spanish foot = 0,2786 m, roman foot = 0,297 m, roman palm = 0,223 m.
18. Is necessary to observe that the Boolean operation of union, subtraction and intersection between solids, the one that has nothing to compare with the intuition is the third. Because the point in common with the solids are inner within the solids.
19. This processing method changes the boolen operations in primitive. A feature is a solid processing event, and it doesn't lose ever its intrinsic characteristics. Dipartimento di Meccanica e Tecnologie Industriali - Università degli Studi di Firenze
20. The paper summarises some aspects of the on-going Doctorate dissertation the author is carrying out at the Politecnico di Bari, and titled *L'unità formale nell'apparecchiatura di sistemi lapidei. Dalla natura sincretica della modellazione digitale alla progettazione/costruzione di elementi architettonici di pietra,* Tutor: Prof. Claudio D'Amato Guerrieri, Politecnico di Bari, PhD Course in Progettazione Architettonica per i Paesi del Mediterraneo, ciclo XVI.

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The calcareous sinter vault of the Nympheum known as «Stadium» at Villa Adriana: Geometry and Statics for an hypothesis of anastilosys

Antonella Falzetti

The great number of the various architectural solutions preserved at Villa Adriana (Hadrian's Villa) does not allow a superficial analysis of the building techniques in Roman times; nor does it attempt supplying inaccurate dates; the wisdom and knowledge in their applying building systems can still be read today in the damaged parts of its walls, in the left-over portions of the coverings, supports and foundations' structures.

Such an incredible and undisputed skill can be acknowleded not only within the large, sumptuous buildings of the Villa doomed for entertainment activities, but also within far more humble ones, often intended for secondary activities, like for example in the building located in the Ninfeo area[1] (see map 1).

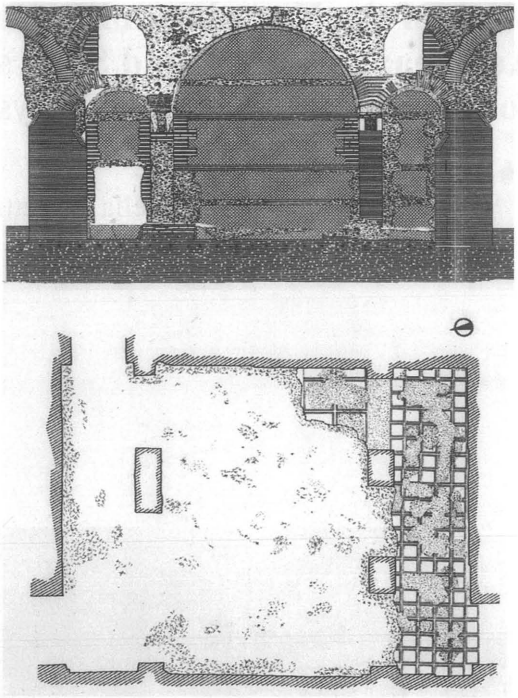
Along the sides of the Ninfeo —for a long time erroneously known as a Stadium,[2] two over-looking buildings appear: one with three exedras and one including the Fish-Pond (Peschiera) and the Cryptoporticus, whose foundation part is obtained by a series of barrel-vaulted intercommunicating covered spaces characterized by a simple, well-ordered set-up.

The central hall consists of an ambient 11,50* 8,80 mts, with a barrel vault in «*opus caementicium*», as well as of two orders of side-corridors also vaulted. The lower ones connecting the main hall with neighbouring ones through openings, while the upper ones being secondary service ways, perhaps *praefurnia*».[3] Such a severe partition of a specific ambient —looking as a one-system one according to the map— is explained by a different flooring; what is left-over today speaks clearly in terms of an «*opus sectile*», which was very much in use at Villa Adriana, however with different dimensions and decoration drawings as to corridors and the central hall. (See map 2)

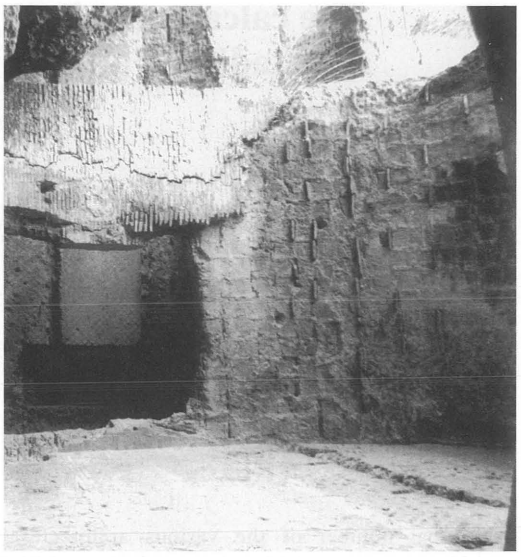


Map 1
The crashed vault before restoration

The ordered asset of walls supporting the building's arched cover shows a building where parallel twilled walls, however different in their garnish, that's to say wall curtains and not walls entirely brick-made. The walls' nucleus, constructed according to building techniques of cement, is finished in «*opus reticulatum*» as to the exterior,



Map 2
Map and prospect of main hall with crashed vault



Map 3
The calcareous sinter vault: please note the tracks of square bricks flatly disposed to adjust with the wooden structures, and of the sloping ones placed in such way

while the intermediate part, the abutment piers supporting the central vault, are in *«opus latericium»*; finishing is by scarfing in *«opus listatum»*.

Building systems supporting the whole vault cover —the large barrel vault as well as the smaller ones— do not show relevant characteristics on their own, given the fact that they represent an element which is technically part of the widely spread traditional building technique for Roman vaults.

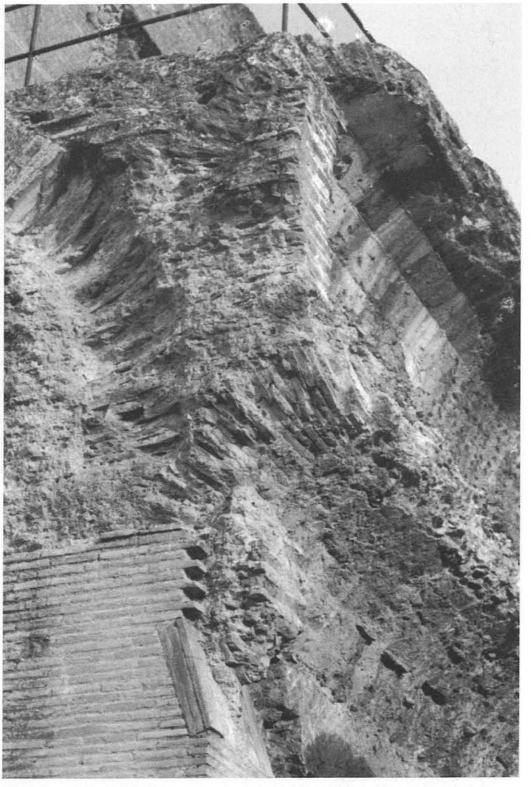
It is still possible to see today —in the intrados soffit of the main vault— tracks of square bricks flatly disposed to adjust with the wooden structures, and of the sloping ones placed in such way as to secure a better coating stiffness, increasing also the scarf with the cement thrown on it (see map 3). The use of a curve-type wall in *«bessali»* proves that a more advanced technique was used in the Empire age, in respect to the one where jet is directly thrown on the wooden structure, like the one applied in the service corridors of the building, considered less important and therefore less esteemed. In this case the soffit scaffolding is obtained starting directly from the vault crest (see map 4).

Roman engineers cleverly used to set abutment piers slightly larger in size in order to include the thickness of the jet containing surface. The protrusion jutting out was then normally used for decorative purposes.[4]

Next to the building façade, as terminal of crest of the barrel vault, there was an arch with accurately set «bipedals».

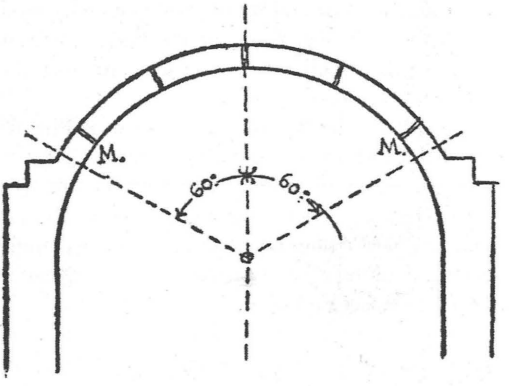
The cement technique and its use find their peak in expression in the construction of barrel vaults, although largely in use before in humble buildings, since considered «more practical and faster».[5] (Lugli 1957, 385).

The vault is the most relevant element of Roman architecture and the dominating one in monuments. The number and variety of its types, although partially inherited by a more ancient art, are the basis of space concepts obtained through an inner connection with building systems harmoniously and mutually solved between aesthetic and static effects.



Map 4
The barrel vault of the side service area. Please note the platform axes on which jet was directly thrown

The deriving effect originating the calcareous sinter vault and its aspects as a structure, have to be approached and interpreted in the light of unavoidable factors, not entirely due to the jet quality; they occur at «crucial moments» —as stressed by Gustavo Giovannoni,[6] altering the structure behaviour up to the point of making a substantial change in the statics' scheme. The expanding cracks and inside detachments within the cement mass split the monolith in big pieces provoking side-pressing actions (see map 5).



Map 5
Schematic drawing of the fractures produced in a *concretum* vault. (Giovannoni [1925] 1972)

At the base of knowledge and constructive roots feeding research and experiments, well-known and widely consolidated notions are to be found; not only, but also experimented and verified both through experience, but also owing to a special intuitive feeling suggesting the best possible exploitation of the structure's specific qualities.

Roman engineers dealing with cement work, and their culture, showed full confidence in the results of endurance of mortar used and mixed with small stone or cotto or marble pieces. The outcome is a compact, solid structure monolithic-looking, while the cohesion between inerts and moltar —as well as the presence in it of a substantial amount of setting binder— guarantees for a remarkable decrease of pressing stresses —typical for such a building system.

This is the specific behaviour of a cut-stone vault or of a vault with a wedged cotter mechanism.

Being aware of such phenomena involves the key to the understanding of the whole building; understanding its shape, its architectural space and static mechanism become the basic reference points as to the understanding of the actual essence of a building.

An in depth knowledge of traditional building materials in use, of work processes, as well as the acknowledgment of a historical stratification, represent the pillars on which to found any reasonment before any intervention to be undertaken can become successful.

In the refined practice of the building technique in calcareous sinter, unforeseen events can therefore occur.

The mediation usually put in act by Roman engineers consists of a few but cautious shrudnesses; the impost structure between he walls' and vaults' masonry is obtained without causing discontinuity in its realization; the size of abutment piers is at times enlarged; the supporting vaults' sections are sometimes unburdened from the cement mass by means of ribbing and unloading arches.

In the specific building under studying consideration here, we notice such exact characteristics, typical of the Roman experience as to optimization and to structures' perfecting.

The Nympheum building is part of a far more articulated architectural set-up, with adjoining rooms also helping the balancing of the vaults' stressing action till the outside walls, nowadays reinforced by brace shoulderings.[7]

The collapse mechanism of the cover is therefore not chargeable to the upsetting of abutment piers, since the structure of the other halls is still today intact. On the contrary, we could hypotize that the abutment piers collapsed under the pressing action of loading charges, having reached an unbearable stressing pressure.

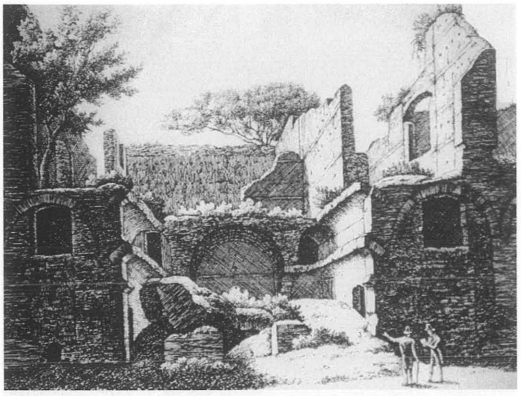
One of the suppositions advanced to explain such happening is based on the assumption that the cover's supporting elements resistant section might have considerably decreased; the cause for this being perhaps two-folded. One is degrading or something different but not unusual, that's to say the picking up of precious materials for possible re-use in other building yards.

We should also remember that the area where Villa Adriana was built has been subject to many and one earthquakes: a seismic quake could have caused the final collapse.

Until the moment when the decision was made on the fixing of the so-called «Stadium»[8] its image was the one of an archaeological ruin well established within people's recalls. The culture and cult for the inherited fragment persisted throughout recent days: a historical and architectural legacy legitimated in its acquired image acknowledgement.[9] (See map 6–7)

On the contrary, now, the romantic attitude towards ruins as ruins having been overcome —there is a tendency to give meaning to reconstruction, allowing the legitimate put-back of lacking parts of buildings.

The opportunity for this specific intervention



Map 6
Hadrian's Villa —the so-called «*Stadium*» with the crashed vault in one of the drawings in A. Penna's book. «*Prospetto del Pulvinare*» Penna A. 1831–1836



Map 7
Hadrian's Villa —the so-called «*Stadium*» with the crashed vault in one of the drawings in P.Gusman's book.. «*La loggia imperiale dello Stadio*» Gusman, P. 1904

—acting within the frame of anastilosys codes— brings into the scene a number of technical and methodological issues. Within this frame the historical building is brought back to a present actuality by the use of traditional materials, the keeping of ancient building characteristics and the use of modern reconstruction techniques.

The most delicate issue in the project, centered on the attempt to re-instate a structural and «linguistic»

ancient unity, can be solved in the persuasion of the need for stopping deterioration of the structure's intact parts as well as of the large vault fragments crashed.

The question is here on how to accept a restoration intervention technically difficult; but not only technically: also «language-wise»: which are in fact the parameters and rules guiding such action of replacing in their original position the crashed parts, so to enable them to find their harmony again within the whole architectural set-up they belong to?[10]

Project makers[11] always had this question in their minds: but this is a risky ground, a stage on which different ideas and debates on restoration theories will take place. The strict rule followed while projecting was the one of re-shaping architectural space, avoiding interventions on the parts lacking serious documentation, like in the case of the façace.[12]

Re-building discretely, suggesting by restricted however essential completions the lost shape of the architectural ensemble: this is the idea, the aim to give the whole place its' archaeological ruin image; not only its hall —under study— but the whole of the preserved structures of the Palace form the scenery, the monument front, which is significant and relevant in the understanding of its architectural importance.

Project makers are convinced —just because of the above— that no lacking parts —though many— are to be filled in by unreal reconstructions, while intervention is needed where statics' problems and up-keeping ones demand action in order to avoid further deterioration.[13] (See map 8–9).

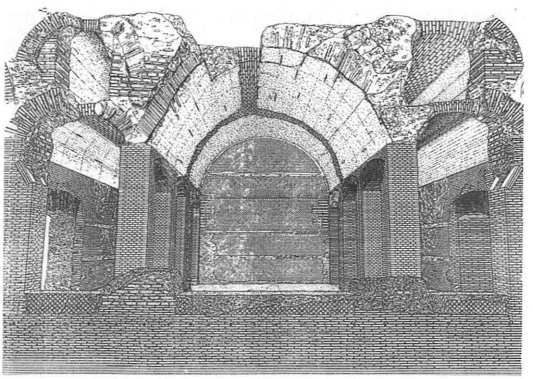
The above described considerations are the code-lines along which the project runs: on one side, the attempt to preserve the architectural value of the building as a legacy of culture and knowledge; on the other side the awareness that interventions and reconstructions deny the statics' set-up of the structure's original system —under study.

On these assumptions the intervention is based: it would be impossible to set-up again the coherent strength of the calcareous sinter vault: therefore one would suggest a new structural contexture considering the present building's conditions, changes and alterations in the course of time.

Transformations' awareness results in a choice: the large vault's fragments, laying on the ground for various centuries, are considered as monoliths still able to keep their original cohesion power.



Map 8
Computer simulation of achieved anastylosis. In the hypothesis advanced by A. Falzetti and A. Giuffrè professor, please not the intention «not to re-build» the façade and the brick wedges in the vault's in the soffit intrados. (TAV. XXII in graduation thesis of Antonella Falzetti)



Map 9
Drawing of achieved anastylosis. (TAV. XXXXIII in graduation thesis of Antonella Falzetti)

This fact requires a new relationship between the structure scheme and the architectural set-up, re-qualified by an upsetting of the statics' system. Such monoliths will have to act as hewn quarry stones with a gravitation structure.

One could object to such solution, as an indiscriminate alteration of the original structure's

characteristics disregarding the protection of the building's identity; but building is not only a question of statics. In this particular case it is just the in-depth knowledge of building techniques and of their limits that suggests and demands a firm attitude in order to solve the problem.

On the other end, once the unavoidable transformations as well as the relevant adjustments incurred in by the calcareous sinter vault between the moment of its actual building to its reaching a natural balance condition acknowledged, the taking into account of such specifications as datas become timely compulsory; pressures on abutment piers occurring at any rate are the direct consequence of the building technique itself; effects due to side stresses do not fade away though being partially absorbed by the setting binder's cohesion power.

In the new structural being, on the contrary, with its stressing actions and relevant pressures —the first thing to do is a re-dimensioning of abutment piers to secure their steadiness and to avoid the risk of their upsetting.

Next comes the placing back of «monoliths», a substantial part of the vaults' system within the Nympheum hall, and the re-composition of the impost pillars' system of the rising barrel vault and of the small side ones.

Such ideas and theories and the strategy for their feasibility should be checked on the spot in the course of building-yard's operational processes, this being the suitable milieu for so doing.

Going back to the problem: the connection between the quality of technical solutions and the reached architectural outcome.

Studies on the achieved result do confirm that this is an extraordinary intervention project however ascertaining that the importance acquired by such restoration project does not necessarily promise quality and accuracy along the actual practical execution processes in the building-yard.

Let's therefore go back here to the basic steps of such work in order to understand its difficulties in execution and to catch the variations —vis-à-vis the given datas— made while working at it on the spot.

For securing the best possible displacing and picking-up of the large vault's parts laying on ground, the first idea occurred was the one of a bad level and of articulated supports.[14]

However, the will for planning every single procedure in detail after serious thinking it over, is subject to independent events that might occur within the building-yard operation. Saving money conceptions prevail on the project itself, showing a quite utilitarian attitude as well as a full confidence in the practical experience on the parts of those who face problems and solve them directly on the spot where works take place.

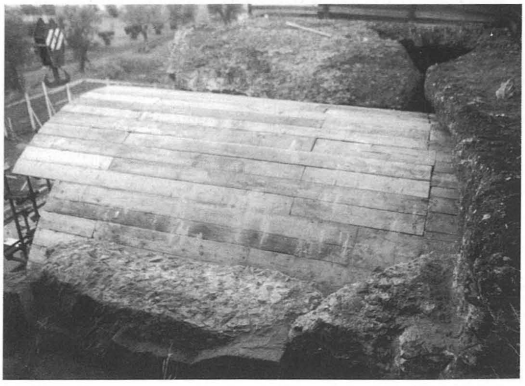
The first large piece, weighting about 62 tons, is picked-up by bad level with wooden staves and steel cables going through two longitudinal holes placed on a provisional wooden structure.

The same happens for the other pieces. (See map 10)



Map 10
Building-yard progress: the first large piece is picked-up and is put-back to its original place

The crashed pieces are put back into position on a suitable soffit scaffolding re-designing the original barrel vault's shape and on newly-built abutment piers; such solution was adopted owing to the need of avoiding the use of bulking bad bedels moving slowly while the piece is being put back to its original place and is hard to remove; the large quarry hewn stone is suspended in perfect shape in correspondence to the barycentre by means of a steel wobbler going through two holes equitably apart from each other and taken to its housing place. (See map 11–12–13)



Map 11
Building-yard progress. The crashed pieces are put back into position on a suitable soffit scaffolding



The lacking abutment piers re-construction —a pillars' and «bipedales» cover-plates system— is obtained by using a modern version of the ancient «emplecton» for re-reading as to consistency and differences building ways in the course of time: a bricks' lining similar to the original ones as to dimensions; the pillars «souls» being in concrete.

The theoretical aim justifies the technique used for the building of new independent elements and not of integrations of part of existing structures.

The reason —not so much linked to a cultural requirement, in this case— has its support on the promise that concrete will respond to quite an extent as a warrant for its resistance to stresses due to heavy loads.

It is important to draw one's attention on how a pragmatic attitude prevails as well as the supreme aim to turn the complexity of the building subject into a programs calculations' instrument easy to apply. Only to the latter we are in fact granting confidence.

The same destiny occurred to reintegration of the large pieces put back in their place.

Although strictly following the rules of restoration codes applied in such a way as to leave a sub-frame in order to secure the individuation of non-original pieces, it was not possible to put in act —owing to problems concerning statics and its steadiness— the linking of locks by cutaway bricks as a «stitching and unstitching» technique to follow the cracking lines of already replaced pieces.



Map 12–13
Building-yard progress. The second big fragment is put back into position on the suitable soffit scaffolding

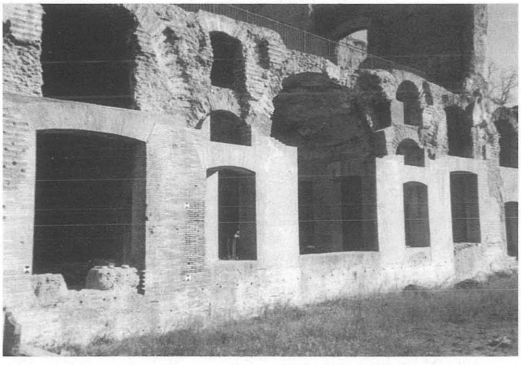
There is a substantial discrepancy, therefore, between the first hypothesis —which was already experimented practically, though— and the fear to insist on a technique which does not meet the safety requirements of the new structure, notwithstanding its deep values.

This cautious attitude is well justified by the dealing with the presence of loads of such entity; practice and experience —essential items for true knowledge— go to the edge of scientific know-how suggesting cautiousness.

Such fact was responsible for the choice of the technique adopted in the attempt not to go against the historical basis of the Roman technique. The necessary fill-in for putting together the original vault's fragments is in calcareous sinter as similar as possible to the ancient one, consisting of a jet of traditional mortar, with lime, pozzolan, inerts and a very small amount of cement and additional materials; the «concretum» pieces are also inter-connected by inox steel bars with improved cohesion power; the continuity between the main barrel vault and the two smaller side-ones —for the great part missing— is also obtained by the use of steel bars and metal nets placed on pattering ground.

The new image obtained witnesses the formal and historical value of the intervention: it is today an acknowledged fact. (See map 14–15)

Through the problems concerning «building conceptions» by traditional techniques and of re-building, one acquires notions on the real essence of the built patrimony.



Map 14
The build after restoration with the integration of original pieces



Map15
The site now, after the work

Awareness of the idea that the need for full respect of the past is the basis of preservation-culture, creates a link between architectural space's structure and form.

The structural interpretation of the building has to be subordinated to building «wisdom and knowledge» of works of the past, without becoming a prominent instrument.

Such final considerations have a question-mark on the intervention: did this restoration-yard —for sure a contribution to building techniques of Roman architecture's knowledge— respect the ethical «must» of re-establishing a true relationship between formal expression and structural reality? Or did technical reasons prevail on unity reasons?

This question does not represent a critique towards the lines adopted in such intervention; it's only a thinking over the strategies used in re-assigning to this very building its entire and specific value as an archaeological witness-legacy.

Notes

1. When looking at the area of the Nympheum-Stadium we can see two overlooking buildings, one on the West side, with three exedras, the other one on the East side called «with Cryptoporticus and Fish-Pond» (Criptoportico and Peschiera). Such building was raised on three levels: the ground floor, corresponding to the garden of the Ninfeo-Stadium; the middle one corresponding to the Criptoportico and the upper one to the Peschiera. In the center, at ground floor, is the main

hall whose vault sank —study subject— with four smaller adjoining-rooms.

2. For many centuries referred to as «Stadium», due to its shape —as explained by A. Penna in the pages of his «Viaggio pittorico della Villa Adriana». «Such building looks as a hippodrome at first sight— and as such I described it; however, having found among its ruins a pond, I have no doubts now: I'm convinced it is a Stadium ...»
G. Nibby, in his «Descrizione della Villa Adriana», states «a limited olive-tree valley —meridian oriented— is called Stadium. Its shorter curve-side looks South ...»
As from 1955 up until the 80's, a number of excavations took place in the area: R. Vighi (1955–1960), S. Aurigemma, A.Hoffmann and the Soprintendenza Archeologica per il Lazio» were in charge of works.
These allowed to prove the mistake in considering it a Stadium. It was therefore since then considered a Ninfeo, an anomalous one though.
3. The whole building is part of the area where high-level entertainment activities used to take place in winter time.
The courtyard of the Peschiera had a high wall all around protecting from wind-blows: an ideal place for walks on sunny winter days; on the lower level a Criptoportico full of light where to walk along on rainy days; the upper area on top of the main hall of the ground floor was perhaps a «triclinium» supplied with «praefurnia» for the heating placed over the small vaults.
4. In Hadrian's age (117–138 a C.) the jet vault building system was improved and changed in order to adjust to temporary requirements, such as a reduction of the armouring or more refined systems setting the jet in horizontal coats of different consistency in order to reduce the fill-in weight, or the putting of brick-arches —not seen— placed according to main curves due to the vault shape, in order to harness and restrain the mix mass.
5. «...we do not know when the calcareous sinter vault came about in Roman architecture, since we lack or miss ancient examples of it with accurate dating. The fact that we find it in use with perfect knowledge of its statics' problems in the large Sillan plants ... proves that it was already in current use since long, with very successful practical results». Lugli 1975, 385
6. The comment notes by Gustavo Giovannoni concern mainly three very specific items characterizing changes in the static mechanism of the calcareous sinter vault: the effect of a giving up when the mass has not yet reached its setting behaviour; deterioration due to weather inclemency and to a lack of maintenance with consequent crumbling; last but not least: the yielding of foundations causing in turn a sudden detachment of parts of the structure itself. Giovannoni [1925] 1972, 44
7. In the middle of the nineteenth century, a number of reinforcement interventions took place within the whole of villa Adriana, under advice of the consulting General Commission for Antiquities and Fine Arts. Works consisted in the building of brace shoulderings and new scarfing of building's main walls. However, a lot of these were removed beginning 1960 and on. This fact should be acknowledged.
8. In 1996 the Soprintendenza Archeologica per il Lazio started re-instating work for replacing in their original position the portions of crashed vault. Such building-yard is intended within the frame of the funds by Ministero per i Beni Culturali e Ambientali for research and planning of anti-seismic works.
9. Villa Adriana's ruins have attracted, in the course of past centuries, the attention of eminent visitors; see engravings by Gian Battista Piranesi, Agostino Penna, P. Gusmann.
10. A preliminary study analysis on how and if to re-instate the vault's big fragments was the subject of the degree work on Restoration's Statics' Problems discussed by Antonella Falzetti at the Rome University La Sapienza —Dept. of Architecture— supervised by professor Antonino Giuffré and Professor Francesco Piccarreta.
Such research work —taken in consideration by the Fine Arts' Soprintendenza as a scientific starting ground, faces transversely all problems involved in a potential intervention: like the consideration and examination of the vault's crashed portions, with special attention drawn on the «where» they were found and of their edges; an estimate of the size of missing parts— the outcome of which shows that they represent an 80% of the whole cover; an evaluation of the mass center in crashed parts through solid samples as well as a weight evaluation of each single element to be removed from where it lays after crash; the individuation of an appropriate slinging system for removing such parts and criteria for the choice of pick-up equipment; restoration and consolidation of actually existing pillars; re-placing fragments where they were originally; re-asset and finishing of lacking parts by cut-placed bricks, to witness the new induced static's mechanism and the elements explaining the filling-in compensation for the lack.
11. General project by: Soprintendenza Archeologica per il Lazio (particularly: M. Lolli Ghetti and P. Baldi —architects in charge). Statics' structural intervention by Professor A. Giuffrè. Building-yard works: R. Righi (at beginning, then S. Gizzi —architect). Antonella Falzetti —architect— cooperated with the Soprintendenza throughout duration of works.
12. Adolf Hoffmann's theory proposing a façade solution

and the re-structuring of the whole Nympheom's garden (Hoffmann 1980).

13. The project of anastilosys suggested in the study-work by Antonella Falzetti (see note 10) emphasizes the idea of the façade not to be built anew, the intervention remaining within the inside of the main prospect.
The computer work simulating what could be the visual impact of the place after the fixing made according to codes and parameters above described, will be of great help in explaining the process.
14. Such research-study and its basis for freeing the area by removing the vault's crashed pieces, tended towards a possible pieces' pick-up without damaging their integrity.
It was necessary for this purpose, to foresee the planning of a simple yard's structure with longitudinal pivots put into proper fitting drillings, connected at the ends by ribbed metal slabs carrying a pivot up to the height of the barycentre of the piece to be moved, to which to link pick-up hooks.

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Late-medieval bridges in the Sicilian country

Giovanni Fatta
Tiziana Campisi

THE ANCIENT BRIDGE IN THE RURAL LANDSCAPE

Singular architectures in the Sicilian landscape, the ancient bridges punctuate its territory, never establishing any conflict with it- in past time and also today- but only perfect integration relationships; it made of minor attention their rule as regard the viability system. If at the time of their construction they constituted fundamental tools for the shifts and the transport of men and goods, they today contribute to define the human installations history, and they represent some permanence that strongly marked the whole rural areas.

Also a superficial examination of the ancient bridges is able to reveal the wish of who designed them as to realize objects only apparently functional to the transit activities; the bridge construction was understood by the collectivity in its doubleness of stable and useful work and object with a strong and attractive image, not only in those rare monumental cases of more spans structures, but also in the late-medieval bridges with one only arch, in which the aesthetical appeal surely is not unimportant as regards the static-functional aspects.

Rather than elementary hand-manufactured articles realized whereas they served for the connection of two road portions, in the design intents it could be checked, instead, the strong visual effect that they had to provoke: the bridge often located in an elevated altimetrical position, it stood out in the surrounding country becoming a sign, the «significante» of a road layout that could not distinguish itself about the volume, an easily recognizable reference point and therefore maintainable during the time, to make precious in the formal treatment and in the detail care. Their numerous representations, pictorial as topographical give evidence of it, that the cartographers, the travellers, the numerous foreign visitors that could know Sicily left us, also at a distance of many centuries as regards the time of these hand-manufactured articles construction; they constituted some elements of great visual impact inside the territory, testimonies of a cultured past to make known to the collectivity and to immortalize for the posterity.(Figure 1) (Figure 2)

A purely engineering work, that has always solicited many ambitions for the form and for the structural conception —surely is not only contemporary the auto-celebrative wish of who designs it— the bridge construction introduced direct relationships with the other natural or artificial components of the context in which it rose, proposing new and more articulated spatial perspectives, images, references and suggestions; its architectural, static, material «quality» would characterize a river site, a natural environment made up by waters, rocks, strong altimetrical differences in height, where sometimes monumental buildings already existed, like castles, mills, thermal baths. All these considerations are further on reinforced if we notice that not rarely the location of these structure-architectures didn't follow the criterion of the maximum useful with the minimum effort, like it could be the river or stream



Figure 1
The Calatrasi bridge, near the town of Roccamena, with double ogival ferrule, after the recent restoration

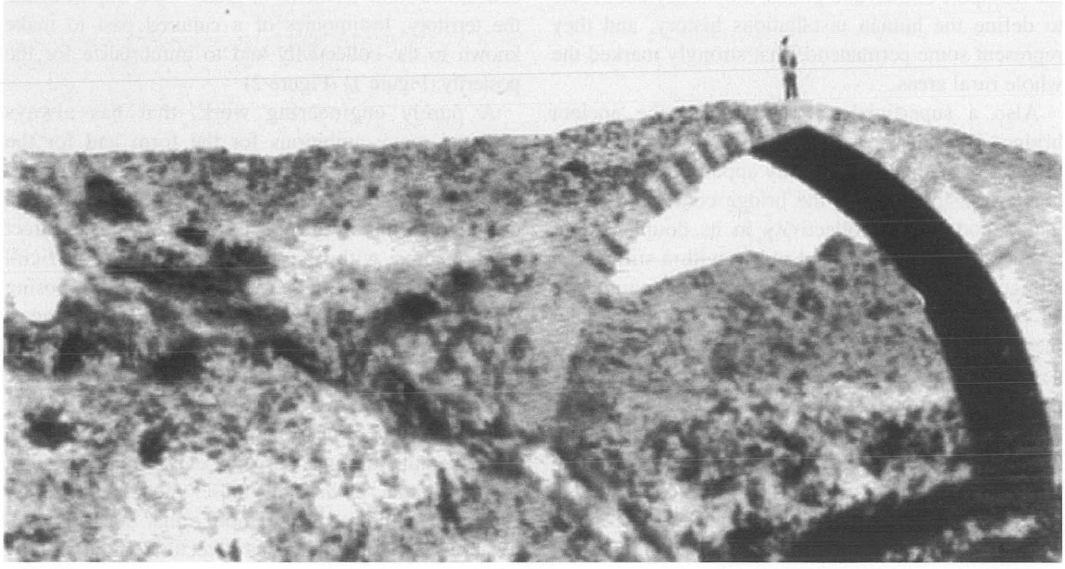


Figure 2
The great bridge with many arcades over the Simeto river, near Adrano. (from Enciclopedia Treccani)

portion that presents the smallest distance between the shores, or that it follows the natural course of the roads to connect; on the contrary, the bridge sometimes stepped over the water course where it widened itself, but to the meantime the major span would improve its proportions and would rise in more panoramic and qualified position, in proximity of rock ridges richer in landscape or near a woody area.

Even though they were built with a declared formal simplicity, the constitutive bridge elements were connected to the traditional way of building in the local ambit and to the style of medieval architecture, a period that for the Sicilian area includes all the XV century, and for some aspects also a consistent part of the following century. The rapid and continuous circulation of knowledge, people and builders happened also through the commercial exchanges or the war and political great events, and through the relationships with the Roman, Arabic and Norman civilization made evident a constructive inheritance that joined Sicily to other geographical areas of the Mediterranean basin, that drew to the same cultural patrimony: in Greece, in Spain, in Jugoslavia, in Turkey —citing only some of these Countries— we can found many hand-manufactured articles not dissimilar about the geometric, type and formal characters. Even if in the communion of figurative and technological appearances, each culture developed however —in the bridges construction— constructive modalities prevalently connected to the «on site» available materials and to the technical and scientific owned knowledges.

The bridges history was also tightly correlated to the viability inside this island; on the basis of a first census, the ancient roads acquaintance has also allowed the recognition of some permanence and furnishes ulterior information about those ones already censussed. In a territory less urbanized, the Romans in imperial epoch realized an efficient road-net, which crossed the island in each direction for the military control and for the exploitation of the resources that Sicily offered. Subsequently, up to the advent of the Arabic domination, some of the existing roads were abandoned and fell in downfall, and with it so happened to many bridges. In the fervour and in the building activism following to the Norman conquest was undertaken a reasoned administration and maintenance of the existing roads, and the king Ruggero improved and realized other infrastructures; we can suppose that on the in existence roads were engaged new bridges; about whose maintenance and consolidation building work begun at the end of the XVIII century we don't know much, but we can affirm that it has allowed their permanence since today.(Figure 3)



Figure 3
The Admiral bridge in Palermo

Geometric and type characters

The new bridges construction in the Early Middle Ages Europe suffered a brake because of the economic and social crisis strongly warned up to the beginning of the second millennium; then it was possible to be witness of a timid raising of the construction activities, but it was hindered by the lack of specialized skilled workers able to realize, applying the «art-rule», those structures able to guarantee, together with civil functions, a military use for withstanding war attacks and to the solicitations owed to the armies passage: in many parts of the Continent we can find often some bridges strengthened, sometimes protected by battlemented towers.

In Sicily the restarting of the civil constructions coincided with the Normans arrival; after many centuries of Arabic domination the local skilled workers were by now moulded to the pointed arch use so, contrary to what happened in the other countries of Italy, this arch type also was employed for the bridge construction. We notice that the same pointed arch was frequently used in the other European regions relapsed under the Arabic dominion (the Orense bridge over the Miño, the Devil bridge at Martorell, in Spain), and also in those places where the taste was already orientated toward the Gothic architecture (bridge of Entraygues, on the Truyere).

If we except very few examples, the Sicilian medieval structures are constituted by only one arch, eventually supported by other smaller arches, whose pointed arch allows to get over great clear-spans; if the banks were next to the water level, it determined a considerable ramps inclination, getting the typical «donkey-back conformation» which characterizes much of these building works.

This constructive solution is certainly simplifier as what concerns the static aspect, because the pointed arch results less pushing on respect the other arch conformations, allowing to save up in the centering and to bear big loads in keystone-arch correspondence; the employ permanence of this type arch, also when the round arches or the reduced curve arches were already broadly diffused in architecture, it would induce to suppose that such choice was not dictated exclusively by technical reasons. The bridges built with pointed arches appeared much more lopped and slender, and also if they were founded at more depressed quotas they would have limited in summit the buildings fillings necessary to reach the wanted quota; so the pointed arch would have stayed prevailing as regards the bridge mass, exalting the perception of the bridge, if not in all his portions, at least in the more characteristic ones.

Besides, also the considerable ramps inclination could be a very important element in the scenic characterization of the bridge, accented also from the conformation of the parapets that followed the same course, or sometimes by the presence – at the top of the ramps having a contrasted inclination - of aedicule, niches, control points, or decorative carving-stone elements.

The ogival conformation also characterized the rare bridges, between those of late-medieval period, in which the monumental aspects had to prevail respect to the other ones: in fact we could find again this conformation with many arcades applied in the construction of two magnificent Sicilian bridges, the Ammiraglio bridge in Palermo and the Saracen bridge over the Simeto river, near the Adrano town. The first one was built in the second quarter of the XII century by the admiral George of Antiochia and since then it constitutes an architecture that qualifies the suburban landscape with its seven acute and degrading arcades; the second, with its majesty and bichromatism, characterizes the rocky surrounding rough landscape. Among the one-span ogival structures, very interesting in relationship to the constructive quality we want to signal the «Saracen» bridge not far from Altavilla Milicia, «Calatrasi» near Roccamena over the Belice river, «San Marco» out from Corleone town, as what concerns the Western portion of the island. (Figure 4) (Figure 5)

The temporal pursuance of the Sicilian Middle Ages beyond the chronological limits recognized in the Western world, made know and spread even in local area the use of the round-arch, all-round or reduced ones, in the architectural works and in the civil constructions; in those bridges risen after the XIV century it becomes frequent the pointed arch substitution by semicircular conformations. We would consider how the round-arch employment reveals itself very convenient when an only arch has to overcome great clear-spans: the ogival conformation use would have carried the arch vertex higher, increasing notably the executive difficulties and the static risk. The same thing could be declared

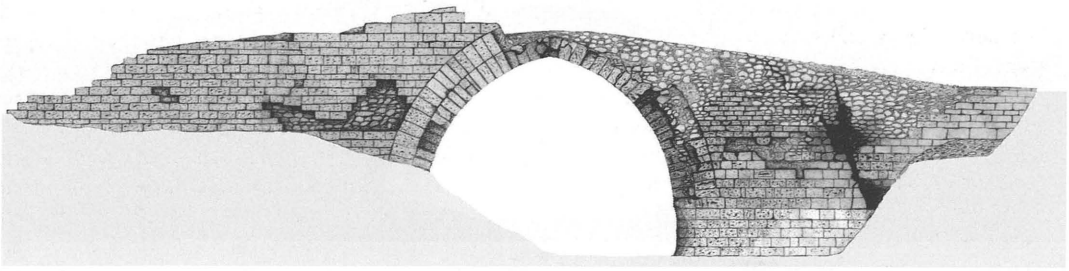


Figure 4
Survey of the «Saraceno» bridge with its decay conditions

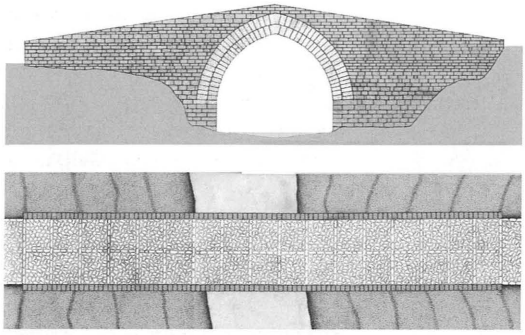


Figure 5
Restoration design of the «Saraceno» bridge. Façade and plan

about those bridges that had to rise in elevated position as regards the access roads, for which were more convenient the reduced in height solutions.

As regard to a presumed indifference about the archivolt geometry design respects to the possible other ones, we retain it finds its justification in the general composition-architectural choices adopted, in the static intuitions that determined the sizing, in the ties imposed by the places, in the harmony and equilibrium relationships between the parts that they wanted to obtain; the bridge had to result sometimes thick or graced, sometimes slender or light and, however, resistant and lasting. Besides, the dimensional relationships imposed to the different parts of the bridge were also determined by the constructive abilities of the skilled workers employ and by the designer technical knowledges.

Already in the immediately following period were used exclusively circular arches, with preference for the reduced curve; it was retained more suited to the new constructive demands and to the mobility requirements in the bridges because, allowing a notable diminution of the ramps inclination, it made these easily passable also by the heavier wagons. In fact, the bridges built with the reduced arch presented ramps with inclination not superior at 10%, very distant from the values reached in the cases of pointed arch, for which the ramps inclination reached easily the 20%. In the Messina area we found a major presence of bridges having reduced-curve arch, with particular reference to the zone that actually was is inserted in the regional Nebrodi Mountains park (Pettineo bridge over the Tusa river and Ninfe bridge over the San Fratello stream).

It is in act a verification about the geometric relationships of the ogives employ in the Sicilian medieval bridges, to set in comparison with the Gothic archs conformations of the bridges in other geographical areas, or in the different architecture type. A parameter that could be measure the «ogive degree» of the arch (to which it corresponds a curve more or less acute) has constituted by the numerical ratio between the real piers distance in the point of the vertical tangency and the diameter of the supposed circular semi-arch. In a first approximation we can consider that this ratio, that is worth 1 for the all round-curve arch, reduced itself to a range included

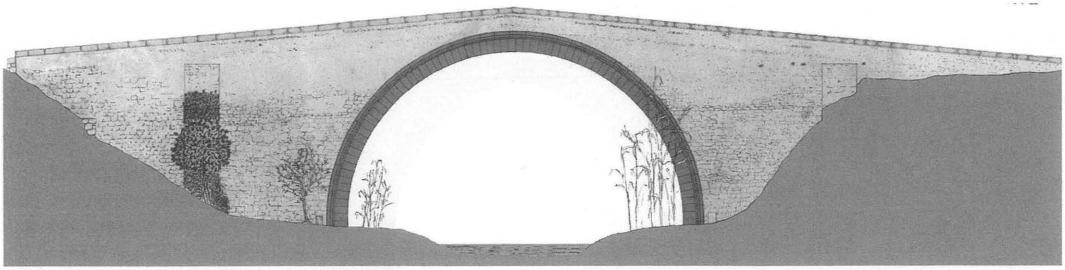


Figure 6
Survey of Risalaimi bridge, with its molding all round arch

between 0.74 and 0.80 for the late-medieval Sicilian bridges. (Figure 6)

The bridge constitutive parts, the materials and the constructive technics

If at first sight the Sicilian medieval bridges present common material-constructive characters, a brought closer investigation shows sufficiently the differences in the materials choice and in the building techniques adopted. Even if they represent natural-stone constructions, for each structure it's possible to recognizes the specificity tied up to the context where it rises, or to the places from which the raw materials employed in the realization derived; the stone abundance in the inner part of the region constitutes the principal resource in the historical building use, and it favoured above all the technical and aesthetical refinement of the stone construction modalities, also in the civil construction ambit. In those rare cases when it was reputed necessary the different materials use, the stone quarry was selected in function of the static role that the stone would have inside the structure, but not a secondary part of the project engagement had the selection of the conformations, size and variety of the stone hewns, in relationship to the chromatic effect that they wanted to obtain, to the portions left at quarry face or that could be finished up by plaster: for these ones, non a great care was required in the constructive modalities of realization. (Figure 7)

The western portion of the island, above all for the zones not distant from the coast, avail itself in prevalence of the conchiferous-limestone use, while in the north-oriental areas and in those next to the mountains, if not well connected from roads to the greater cities, we find the compact stone, often having a calcareous nature, rarely siliceous, lavic in the Etna area; the brick use, discovered only in one case, could be the result of consolidation interventions or of a reconstruction happened beyond our temporal limit.

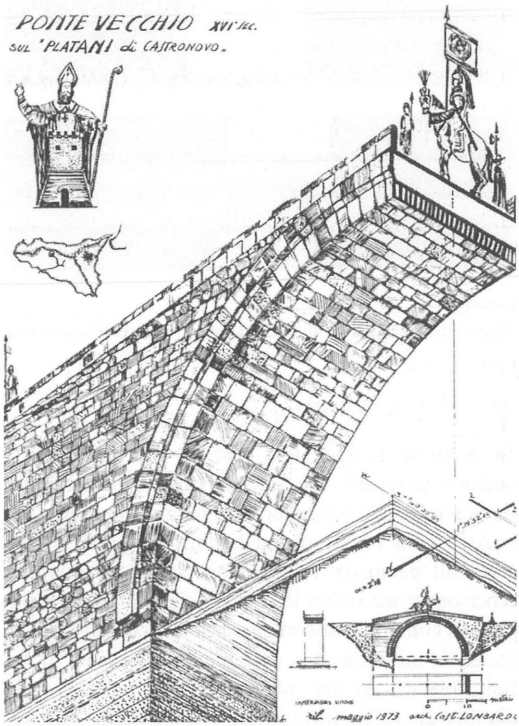


Figure 7
Drawing survey of «Ponte Vecchio», near the town of Castronovo di Sicilia. (from Lombardo C.)

The conchiferous-limestones extracted in the western Sicily coastal areas constitute almost the historical built totality of the island, even if it's of current or monumental type. The good quality of many of these stones has recommended its use above all for the vaults apparatus and for those parts to mould and finish up carefully, in consideration of the facility to work the material to the ax and to the saw getting perfectly plain surfaces and alive edges sufficiently resistant.

The arches of façade that define the armlet are always particularly finished and distinguishable by the rest of the structure, thought in the simplicity of the whole, the radial voussoirs present from 5 to 6 carved faced, and in many cases there are more formal sophisticated treatments by the formation of moulding that follows the armlet extrados. In the bridges with ogival arcade we have always found a double over imposed ferrule; the superior one projects over the inferior one by a 5cm prominence in a sharp edge; so we succeeded in determining a shading effect along the contour of the ogive that made the structure precious approaching it to the coeval architectures.

On the contrary, there are simple or double ferrule in the bridges with all round arcade; in the second case the inferior armlet acting as centre of the overhanging arcade seems the most finished, because, as visibly free intrados, more than the other contributes to the aesthetical connotation of the bridge; in these cases the projection reaches 20cm and has a strongly bevelled edge.

The arcade is generally constituted by barrel-vault in well square and toothing hewn stones with drawn up joints and pseudo-isodom arrangement, with a particular care for the visible arches where the apparatus is in a better quality about thinness and course of the joints, uniformity and number of carved faces of the radial voussoirs; among these some hewn stones have a prevailing transversal dimension to realize a deep indentation inside the rest of the vault. They are rare the cases in which the portion of in-closed vault between the two external arches presents a chaotic apparatus just in onlined stone. We signal for boldness, elegance and structural originality the Caccamo bridge, on the S. Leonardo river, built in 1307 by Manfredi I Chiaramonte. This bridge has all-round vault, with span 20m long, constituted by three groins 1m thick; it allowed a notable structure lightening of probable Roman derivation, thanks to the two transversal little vaults in small hewn stones. (Figure 8)

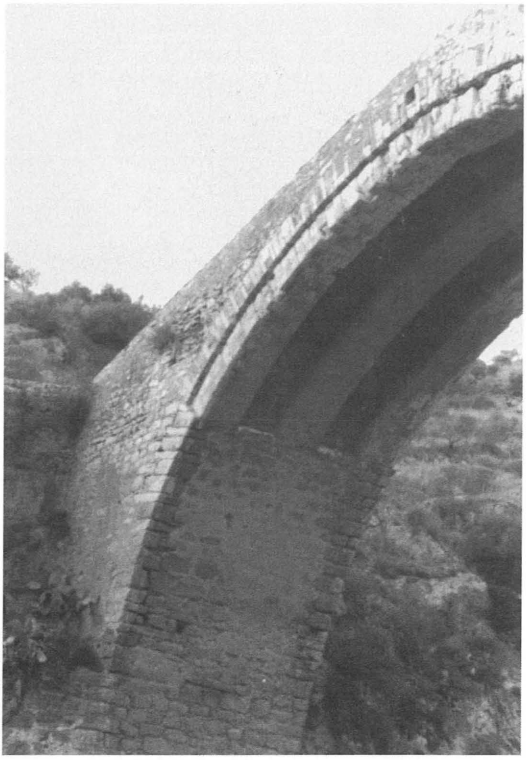


Figure 8
Caccamo bridge. We can see the three great ribs, constituting the main arch

The groins start with a 45° degrees angle and lean on false vault, because the hewn stone are not radially disposed but with light inclination to the horizontal line; on the external arcade faces there is a double armlet for the only length of the rips. After the construction of the Rosamarina dike in 1994 the bridge has been completely submerged.

The hanging in outlined heap of stones seems not much diffused, with a simple nod of disposition in lined up rows; in such a case, is not rare on the vault and on the prospectus to find some of finishing plaster traces, which would motivate the lack of formal care in the realization of this apparatus; also to limit the maintenance in forecast of the strong erosion caused by wind and water (rainwater and current), so the intention of leaving the masonry on sight was obvious, possibly finished in each part. (Figure 9)



Figure 9
The break of carved hewn stones wall, shows the nucleus, constituted by shapeless stones

The basement part mostly subjected to erosion by the torrential water were constituted by a more compact and resistant stone, and also in greater hewn stones: we frequent find stony reinstatement and/or substitution because of the erosion phenomenon during the time. The shoulders were built with a nucleus in sack masonry: between the two external hangings in finely carved stone in its faces and its edges it's operated a throw of fully grown concrete of river pebbles of varied speckling, and it was made a shapeless heap of stones and mortar of lime, made hydraulic by *pozzolana* and brick-dust. In many cases, the collapse of portions of the buildings hangings has allowed to investigate about the masonry composition constituting the nucleus of the same hangings, and to verify in which measure the toothing of the hewn stones of façade in the internal nucleus of filling, were maken.

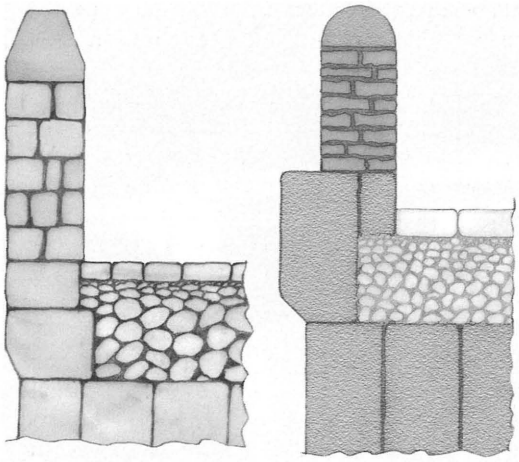
It's believable that, however, this procedure was a normal administration, as consolidated constructive technique in Roman epoch and become in centuries one of the referable precepts to the «rule of art».

The hangings were always thick and deprived of lightening systems or hollows, except that one in the aforesaid bridge in Caccamo, where we found an accessible vain through the smallest arcade; it is extended deeply inside one of the hangings, in longitudinal direction to the bridge; we are not able to know if it serves for lightening or other functions. In frequent cases of dissimetry between the banks, an arcade was sometimes founded directly on the rock, while the other leaned on artificial unwrapped at plinth basament; this one was provided with a rostrum of triangular base protecting the same hanging, as a wing wall, in order to a better canalisation of the current waters.

Very interesting is the flooring examination of the medieval insular bridges, constituted in all the analysed cases by a cobbled paving whose elements were probably retrieved in place from the river bed. From the large original residual parts is generally possible to see the rectangular mesh sketch, made up of guides in calcareous compact stones outlined in parallelepiped form which closes the fields where are drowned the round pebbles. More precise variations on the same theme foresaw, like the Admiral bridge in Palermo, that also the diagonal of each rectangle were made in the same way like the guides. This kind of flooring was similar to that one often used for the roads, or alleys, inside courts, diffused in many Sicilian urban centres of any order and degree.

The cobbled paving, like other before analysed parts of the construction, is directly exposed as to the atmospheric agent (washing away of the mortar joints and erosion of the pebbles and stony plates) as to the mechanical solicitation at the transit of pedestrian animals and wagons; it was destined to frequent substitutions and partial reinstatements, it required periodic interventions of ordinary maintenance and revision which only in part are recognizable after a precise examination. In a case of strong inclination the flooring is spaced out by steps and the cobbled paving is chaotic, not framed within geometric panels.

The parapet was the necessary functional complexion in relationship with the altimetries of the places, that constituted with its not negligible building portion an important element in the formal definition of the whole bridge. It was generally built with shapeless heap of stones, and mortar finished up by a top cord of hewn stones worked in semicircular section. Many solutions have been found, which used for the small parapet hewn stones of limestone square, disposed in rows following the ramps inclination; the aesthetical question of the link between the horizontal rows of the main structure and the titled one of the parapet has been resolved by the use in many layers of hewn stones of opportune conformation. The 40 cm thick parapets were surmounted by shaped hewn stones which ended in different ways, from a straight surface to a trapezoidal section, from slightly beleved angles with hewn stone of triangular section. (Figures 10, 11)



Figures 10,11
Constructive particulars of bridge parapets

The actual state. The degrade, risks and objectives

As often it happens for those buildings thought of «minor importance» that, when their utility and function left off they are neglected and set out for a slow but inexorable decline, so it also happens for the old watermills, small farms, bridges in disuse and many other manufactured articles. If any of these is known only by who looks for them on purpose, on the contrary the ancient bridges have also a landscape valence because of their position and the place they rise in, and they're almost the few buildings that for their intrinsic original solidity remain for many centuries in spite of meteorological events, vandalism, carelessness.

The new roads realization, little by little, made unnecessary the ancient street layouts use, and with them some bridges, considered less safe and unsuitable to the actual uses and to the transport means transiting there. About the configuration of the ancient roads, or the communications renewal in Sicily, there are many medieval bridges smothered by the proximity of new bridges and viaducts, railways or roads, in iron or reinforced concrete; this circumstance changes the whole perception of the ancient hand manufactured article, creating conflictual perspectives and backdrops on which these architectures stand out, determining confusion and chaotic perceptions of the surrounding. (Figures 12,13)

The extreme case is constituted by the already quoted bridge in Caccamo, for which in occasion of the Rosamarina dyke project it was discussed for a long time (almost twenty years) if and how to get off and reassemble it elsewhere: serious hydraulic necessities about the cities and countries closed this poor debate and the bridge is actually drowned with all the relatives risks of irrecoverableness.

The interest for the most ancient bridges never failed until the XIX century, with substantial maintenance and restoration interventions of those that required sudden remedies, in some case due to land slides and foundation backdrops causing partial collapses, to these works of consolidation is tied up a great part of the metallic chains introductions.

The loss of the original function has allowed some improper uses in these ancient structures, someone by now relegated to entertain water reservoirs support, that is, exposed to the progressive removal of the constitutive parts of the structure, employed again for new construction or stolen if precious.

The lack of any elementary maintenance has facilitated many degrade phenomenon imputable to the erosion of the parts subjected to the action of the water or wind, such as base zones and in correspondence of the solution of continuity, such as prominences between the ferrules of the arches, preferential routs of slide for the rainwater, and also of superficial deposits; phenomenon of damp is observed about capillary reclimbing, rainy infiltrations, faciliting the taking root of biological patina and weed, with consequent damages for the break up of stony materials caused by the radical apparatus of the latter.

Besides, is not rare that the buildings hangings, the nucleus and the vaults have suffered partial collapses, due to the hewn stones un-cohesion caused by the washing away of the mortar joints, of the floorings partly vast-off or ruined by bushes and spontaneous plants.

The damages caused by abandonment are lied up to those baited by hasty interventions and not much respectful of the formal and constructive original characteristics, recently operated: it has been indiscriminately used the cement in the parts of masonry reconstruction, or in finishing up the hangings, or in covering the ramps flooring and the parapet inside, the recovering of the parapet little



Figure 12
Medieval bridge example suffocated by an actual concrete bridge

walls with bituminous scabbards; besides baiting serious damages in different parts of the bridges, it had sometimes notably altered the external aspect, preventing the recognition of the different buildings tones weavings, of the mouldings and prominences.

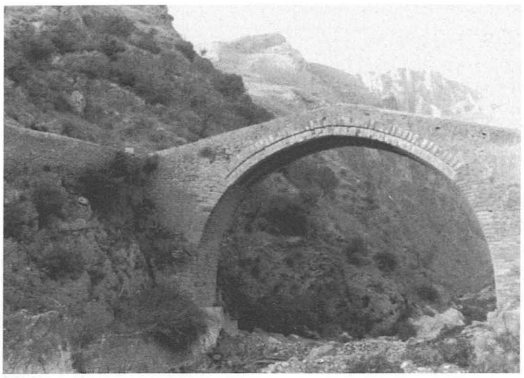
The cement works acted on the river bed didn't save up the bridges, whose arches are sometimes forced to put on shoulders in reinforced concrete, to which they are connected through metallic bars, with the consequent oxidation degrades.

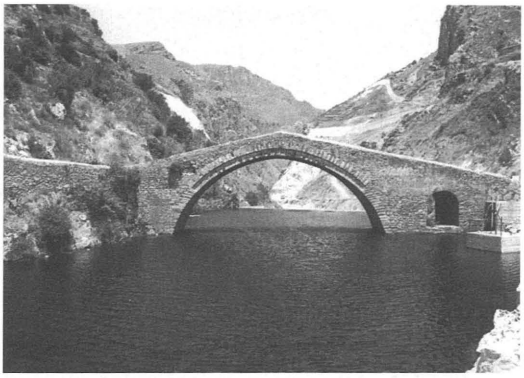


Figure 13
The highway viaduct impends over the «Saraceno» bridge, near Altavilla Milicia

It's not easy and perhaps not even useful, for the ancient bridges to hypothesize a compatible function. Some years ago in Sicily, and we know that it happened also in other European countries, a great campaign begun in order to awaken citizen to the rural environment, it was carried up by voluntaries associations and the same public administration which recognize their social value and the possibility of economic development.

They try to equip the most suggestive places and the most esteemed environ manufactured articles of elevated historical content and testimony of human installation, in pedestrian, equestrian and cicly runs which allow people to use historical and naturalistic resources, focusing on the institution of urban, fluvial





Figures 14,15
The Caccamo bridge, before it was submerged and during the Rosamarina dike filling

and inter-municipal parks and natural reserves, and on the rural vocation of many places of the Sicilian territory, together with ancient mills, paper mills, farms and beams. (Figures 14, 15)

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Shifting Grounds: The effects of altered modes of research and development in construction

John E. Fernández

Since the beginning of the coordinated enterprise of construction, expert knowledge of building materials and supporting technologies have been conveyed from one cultural context to the next. Transfer through time, across geographic and societal boundaries and from knowledgeable practitioners to novices in building construction, has accelerated with improved methods for disseminating the myriad types of technical advances generated within the last several centuries. A variety of media has facilitated this transfer. Among many methods employed through the ages, the buildings themselves have been primary artifacts along with architectural treatises, published papers and a continuing legacy of the instruction in craft and trade skills. From the ancients through the 19th century, this combination of knowledge streams conferred upon the architect and builder an anchoring in the complex interdependence of technical issues for making buildings while providing a rich record of proven field experience. Only recently has knowledge of technologies been transferred through a coordinated structure of peer-reviewed journals and accepted standards and codes established through empirical methods and theoretical models. This recently developed mode of communication has been the result of the specialization of disciplines based in the sciences and charged with technical research in various building science subjects.

While innovation in construction has always been, and to some extent continues to be, the result of the local confluence of a great diversity of economic, technological and cultural forces, the context for that innovation, and its mode of dissemination, has steadily shifted from a synthesis of architectural priorities and proven techniques to a process of increasing intellectual articulation within separately guided scientific disciplines. Beginning in the mid 18th century, the locus of innovation slowly began to shift from the trade guilds, craft workshops and construction site itself to the nascent production plant of the industrial revolution, and later the scientific laboratory. For the first time, the process of the development of materials for construction was displaced to entities —the research laboratory and industrial production facility— whose primary modes of investigation are regulated, not by the multifaceted discourse of architectural thought and construction logic, but by singular procedures of the scientific method. This paper investigates the relationship between this shift, new modes of information dissemination and the effect on the current state of diversity of methods and materials for construction. In particular, the advances in materials sciences and engineering are used to distinguish between past streams of innovation and the current state of affairs.

Architectural Treatises and Scientific Papers

Specialized knowledge has often found equally specialized methods for its communication from

one group to another. Knowledge, of any kind, but especially technical and scientific knowledge is retained and augmented in societies primarily through the active communication between research entities and interested parties. In addition, knowledge is also disseminated through time from one generation to the next using a great variety of media meant to transcend the friction between generations and the risk of loss. The particular vehicle for both of these kinds of communication —from experts to nonexperts and one generation to the next— varies with the historical period, culture, economy, language and particular technologies of the society. In addition, knowledge may also travel between distinct cultures and societies, again through time and space, traversing belief systems, political and social hierarchies and geography alike. Dissemination of knowledge has, until recently, been facilitated most easily between parties within the same culture and regional context. With the globalization of communication and the spread of international research journals and web-based data banks, this regionalism has been forever altered.

The advances of architectural technologies, as a particular body of technical and design knowledge, have also been transmitted through the ages in a great variety of ways. These methods have also changed dramatically over time and continue to evolve. The type of communication media used has been very much related to the type of architecture in question. Knowledge of the architecture of the ruling classes and governing institutions has always traveled through privileged conduits. Knowledge of vernacular, popular and regionally distinctive architecture, especially that of residential and agrarian buildings, has been, again until recently, transferred by tradition —word of mouth and first-hand experience. This paper concerns itself with the knowledge derived from buildings built for these ruling classes and institutions, as these buildings have served as the primary focus of innovative construction and material techniques.

Early in the development of construction technologies and throughout the pre-industrial world, buildings themselves played the dominant role in exemplifying accepted practice and transmitting techniques to a select design audience. Throughout the ancient world, into the medieval period and the renaissance and continuing through the industrial revolution, the most widely recognized buildings were instrumental in providing knowledge of architectural technologies to successive generations of engineers and architects. This was accomplished and popularized through the tradition of the architect's travels to sites and buildings of recognized significance. Palladio traveled to Rome in the 16th century to visit the «stupendous ruins» of the Romans (Palladio 1570). The great architectural pilgrimages of the 18th and 19th centuries included travel to Rome, Greece and Egypt and beyond. These journeys were motivated by the balanced need to learn of architectural orders as well as construction practices. The pantheon not only told one of the proportional aspirations of the Roman designers but also of their mastery of concrete technologies. The Roman aqueduct at Segovia in Spain, Figure 1, among many others, exemplified the elegance and extraordinary construction technique of the Roman arch.

Augmenting the buildings, the architectural treatise and associated publications also played an important role in documenting advances in construction technique, codifying best practice and disseminating

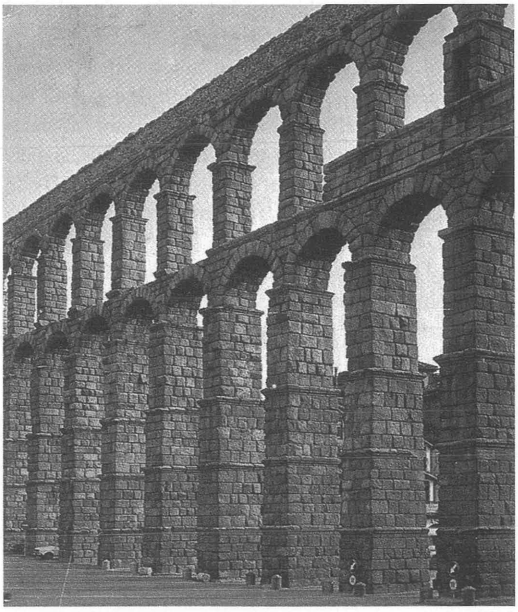


Figure 1
Roman Aqueduct, Segovia, Spain. View of the tallest portion of the structure

findings geographically and temporally. The writings of Vitruvius, Alberti and Palladio exemplify this technique for communication of architectural principles as well as construction techniques. The kind of knowledge contained within was rendered through text, architectural drawings, construction sketches and diagrams. As a result, the treatise has been an important element in the communication of process, as well as guiding principles.

In fact, beginning with Vitruvius, not only the techniques of construction but also the inherent properties of building materials have been an important component of architectural learning. Vitruvius stressed the importance of understanding the relevant physical properties of the primary materials of construction as a fundamental aspect of the act of building.

> All things therefore appear to be made up and produced by the coming together of these elements, so that they have been distributed by nature among an infinite number of kinds of things. Hence I believe it right to treat of the diversity and practical peculiarities of these things as well as of the qualities which they exhibit in buildings, so that persons who are intending to build may understand them and so make no mistake, but may gather materials which are suitable to use in their buildings. (Vitruvius, Granger 1999)

Vitruvius' audience is those *persons intending to build*. Clearly he has positioned his writing as a source of knowledge for the present and the future including both a discourse on architectural design and construction technique.

> Hence I thought I should compose with the utmost care a comprehensive work on the art of building and its methods in the belief that the future will not be ungrateful for this service to the world. (Vitruvius, Book VI, Preface)

His writing demonstrates this by including examples of procedures and descriptions of material properties, as they were known at that time. It is important to note that in his writing all of the information comes from scenarios in the field —on the site of construction. The knowledge of materials for construction is centered on the act of building.

The treatise through much of history was engaged in presenting a more or less complete picture of the discipline of architecture; design principles and building techniques. The topics typically addressed included technical discussions of methods of construction, strategies for good practice on the construction site, descriptions of useful material properties and many other facts regarding the process of realizing a building. However, the technical information gathered within these documents spoke to a set of generalized and descriptive relations rather than results gathered from empirical studies of the kind that characterize modern science. The relations illustrated within treatises produced before the 18th century did not contain the kinds of investigations that would characterize the scientific revolution of Galileo and Copernicus and the regulated process of the scientific method. Therefore, the technology of construction was presented as a set of relations based in «common sense», construction experience and rules of beauty or notions of propriety rather than the quantifiable behavior of materials under performance loading.

The writings of Alberti, Palladio, Carlo Fontana and others demonstrate this character quite well. For example, Fontana, writing in 1694 (Fontana, 1694), addressed problems in the cracking of St. Peter's dome through a postulation of solutions that used geometric relations to establish the requisite needs of *solidity* (Perez-Gomez, 1994). Fontana used this rationale for uncovering divine relations in the physical construct and design conception of the church. Alberti, also intent on providing useful information on building includes diagrams of typical masonry wall construction, timber details and other mundane construction details as well as suggestions on construction that depend quite a lot on common sense, or at least reasonable conclusions.

> Once the lines and angles of the trenches have been marked out, it would be good if we could use the same vision and intuition that a certain Spaniard was recently reported to have had: he was allegedly able to divine the veins of water snaking deep within the earth as clearly as if they were flowing on the surface . . . The ancients used to say, «Dig until you reach solid ground, and God be with you» (Alberti 1550).

And while the 18th century was to bring a revolution in the nature of technical knowledge and the methods of investigation, the descriptive treatise was to survive through many centuries and continues today.



Figure 2
Portrait of Leon Batista Alberti, «gentil huomo Fiorentino». (On the Art of Building in Ten Books, Alberti)

For example, in the early 18th century, parallel to advances in science, several efforts were underway to inaugurate a newly revived renaissance sensibility in architecture. Writing in his *Vitruvius Britannicus*, Colen Campbell (1676–1729) argued the right of British architecture to assume the mantle of the ancient and renaissance orders. He raised Indigo Jones to the position of rightful heir to the perfection of Palladio's architecture. This kind of treatise did not wane over time. In fact, the writings of architects today strongly continue to argue for the legitimacy of particular forms and design approaches solely based on non-technical issues. During the passage of centuries, one type of knowledge did not fully succumb to another. While science was developing its own methods and beginning to publish findings, the architectural treatise did not lose its power to establish artistic authority.

However, individual thinkers and vanguard scientists of the time were initiating an irreversible

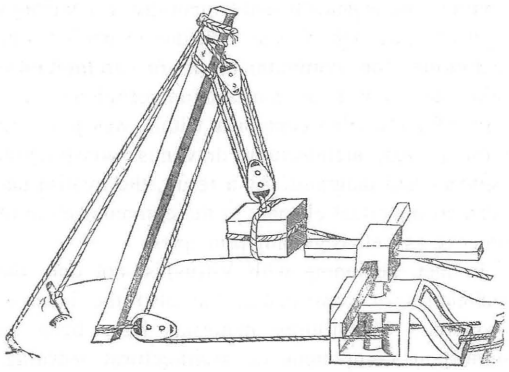


Figure 3
Lifting tackle composed of a post, lines, pulleys, and winch. (On the Art of Building in Ten Books, Alberti)

germination of principles based on observation and experimentation. During the early eighteenth century discoveries made of the strength of materials began to find their way into scientific papers and architectural treatises. These discoveries, while still presented very much in the tradition of Vitruvius, Alberti and Palladio, used a nascent scientific method and newly developed empirical strategies for reaching conclusions directed toward rapid introduction into engineering and architectural applications. These efforts were fundamentally influenced by the mathematical formulations brought to the study of the strength of materials and statics by Galileo. While the direction was a productive one, it would be some time before the most fundamental problems in statics and strength of materials were to be solved. Eventually novel solutions surfaced to replace the «pronounced failure in the normal problem-solving activity» of predicting the performance of structural elements. (Kuhn 1996) The intent of these writings was still clearly toward augmenting the tools available to builders in achieving physical constructs. The methods used to reach these conclusions were of a very different kind than ever used before, that of the construction of a world fully described in terms of abstract geometry and numerical quanta.

As a clear shift toward scientific principles, Gautier of the newly formed *Corps des Ponts et Chausees* published a treatise on bridges during the first third of the 18th century. His *Traité* (Gautier, 1727) went so

far as to advocate that architecture was founded on principles of mechanics and empirically determined strength of materials. His eclipse of previous methods for establishing the «correct» proportions of individual structural members helped to bring forward the idea that form was dependent on physical phenomena rather than «rules» of ideal proportion or beauty.

A Functional Architecture

That is, the description of architecture, both as a process of production and the embodiment of physical proportional perfection was achieved through a treatment of subjects as varied as mathematical constants of the ancient orders and specific recommendations on the processing, placement and finishing of building materials. For many centuries, the discussion of architecture could not be considered in terms in which this synthesis was not referred to. While this clearly led to extraordinary results, especially in terms of advances reached through a combination of construction experience as well as an enhanced intuition aided by the learning that comes from a first-hand knowledge of the properties of building materials, it could not advance a generalized understanding of the forces that contributed to the performance of buildings through their individual components. It would take a search of several centuries, beginning with Galileo's attempts to mathematically describe the essential elements of statics and the strength of materials, to arrive at the beginnings of a concerted effort to understand the underlying forces affecting architectural components.

It is useful to remind oneself that technology, as an expression of the human ability to configure tools and develop processes, has always accompanied the species. Science has not. Science is the result of formulations of methods and conclusions reached through the application of the scientific method. Also, it is important to note that the industrial revolution was a revolution for society, industry and national economies but not a revolution, in the true sense of that word, for technology or science. Contrary to popular understanding, the scientific and technological progress of that time was clearly incremental (Bassalla, 1999). Improvements in machinery design, the harnessing of useful work from energy with the development of the steam and internal combustion engines, the rise of organic chemistry, the invention of electric lighting and communications, all contributed to revolutionary social changes through incremental scientific and technological advances. During the industrial revolution the manufacture of architectural materials was transferred from the agrarian setting of the nonindustrial countryside to the setting of the urban factory.

While there occurred a social revolution in the displacement of centers of production through the centralization of manufacturing capacity, the steps taken by scientists and technologists were incremental and slow. However, the contributions of Mariotte, Musschonbrek, Gautier, Soufflot and later, Perronet others brought architectural technologies, especially those concerned with statics and the strength of materials toward a calibration of the dominant factors for determining correct form and use of materials. Before the work of these individuals, the truths inherent in geometric relations —defined as originating in notions of both efficient form and divine representation— dominated the work of leading architects and engineers. As a result of a reconsideration of the deterministic import of geometry, and a newly gained set of empirical and theoretical tools, the forms of architecture were now to be substantially influenced by a growing articulation of physical principles. Culminating in the presentation, to the Royal Academy of Science, of Charles-Auguste Coulomb's paper «On the Application of the Rules of Maximums and Minimums to Some Problems of Statics Relative to Architecture», (Coulomb, 1773) the aspirations of many engineers and architects intent on applying mathematical relations to real-world scenarios was finally achieved. By the end of the 18th century the science of architecture and engineering had finally overtaken the philosophy of form. As Perez-Gomez writes in *Architecture and the Crisis of Modern Science*,

> Finally, architectural reality could be truly functionalized, allowing for an effective substitution of mathematical rules for the experience derived from building practice. Building practice could now be effectively controlled and dominated by «theory». The *Institut National*, founded after the Revolution, «solemnly» adopted the conclusions of Girard's work in a report signed by Coulomb and Prony (Perez, Gomez 1994, 266–7).

These advances led to the establishment of two conditions that were to change the nature of the relationship between the architect, construction techniques and the materials of construction. First, the delineation of the discrete domains of study for the inventor of construction techniques and materials meant that the non-architect could make strides forward in improving, and profiting, from new technologies for realizing buildings. Second, these individuals would begin the process of the founding of two of the dominant organs for research, development and manufacturing of building materials; the private corporation and the academic building science research entity.

In delivering the fruits of the theoretical work of the 18th century, researchers of architectural and engineering situations were still occupied, as they are today, with the need to synthesize the lessons of quantitative analysis with the messy reality of the real world. To achieve this synthesis, the researchers of the time needed to employ the regulated steps of the scientific method.

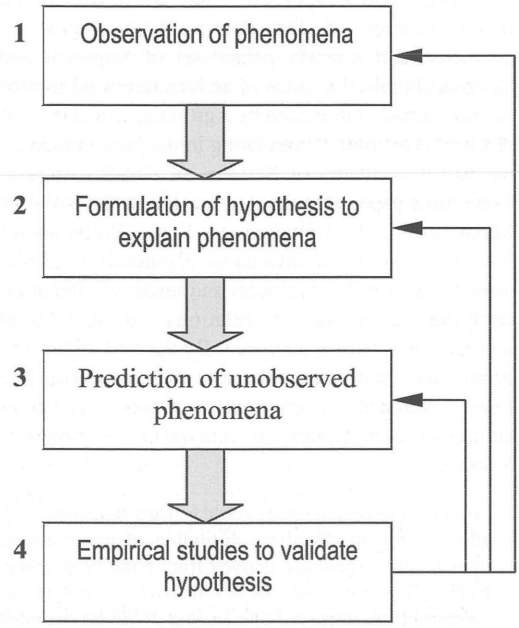


Figure 4
Diagram of the scientific method

The scientific method, in its simplest form, consists of four discrete steps generally taken sequentially. The observation of phenomena precedes the formulation of a hypothesis. These two steps often lead to speculation regarding other unobserved phenomena. The final step requires testing —empirical proof— that the hypothesis has correctly explained the essential elements of the phenomena.

Independent inventors sought in the scientific method an unassailable strategy for entering into new and potentially profitable enterprises. The individuals that took over control of the development of building materials were those entrepreneurs and inventors that were often only mildly associated with the technology of building. The likes of Aspdin, Monier, even Paxton were concerned with the development of a material through experimentation and eventually characterization. The methods of science were the methods employed by this group of inventors. With the use of the scientific method the slow shift toward empirical research for architectural materials began. These individuals and others came to be the front wave of the establishment of the large modern multinational corporation. As a result of this dynamic, these large corporations have become the stewards, and the owners, of real material innovation including that applied to architecture. The companies most responsible for changing the materials landscape of contemporary architecture have been the larger chemical companies, steel and aluminum refiners and fabricators and glass companies. Owens Corning, Dupont, LaFarge, Pilkington, Saint-Gobain, Bethlehem Steel and many others have been setting the pace for the invention and development of new materials and enhancements of existing materials for industry. The primary vehicle for achieving this sustained dominance has been the corporate research laboratory. Architecture has seen a great deal of transfer of materials and techniques from an assortment of industries bolstered by the fruits of research and development.

The Modern Research Laboratory and the Materials of Construction

Beginning with the rise of the scientific method, an interesting and influential process began to overtake traditional methods for making incremental

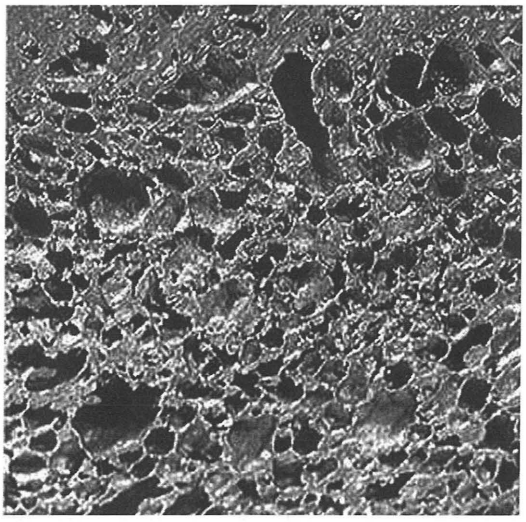


Figure 5
Foamed Aluminum



Figure 6
Stainless steel exterior envelope component

improvements in architectural technologies and capturing these innovations within the knowledge-base of the architect. Rather than the construction site serving as the primary location for the development of innovative material formulations for buildings, this role was shifted to the laboratory; not all at once and not with respect to all construction materials. However, increasingly through the latter half of the 19th century and into the 20th, materials conceived of at a distance from the construction site and for applications not related to architecture were being redirected toward building components. During the early twentieth century, the research laboratory began to act as the primary location of this kind of innovation.

The modern research laboratory began its history as a corporate sponsored facility born of the activities of individual inventors and entrepreneurs that founded research active companies. The first research laboratories were established in Germany during the last half of the 19th century to serve synthetic dye manufacturers. England and the United States were to follow closely behind with a number of labs established by the first quarter of the century. Thomas Alva Edison's workshops at Menlo Park (established 1876) and West Orange, New Jersey (established 1887) were the precursors to the modern industrial research laboratory. These workshops and several companies founded by Edison were organized into the General Electric Corporation. In 1901 General Electric founded its research laboratory and within the next 12 years Kodak, Dupont, the Bell System and others followed suit. By 1930, 526 American companies had established research facilities. IBM's first research lab was established in 1945. By the early 1980s, 11,000 American companies supported laboratory facilities. (Basalla 1988, 126)

These early labs established the precedent for diversification of products and an initiation of corporate sponsored invention. They also initiated an era in which patent law became a prime insulator from competition. The argument that these facilities accomplished as much in terms of sheltering commercial rights as catalyzing original research is a strong position bolstered by significant research. However, these labs did continue to accelerate changes in the physical components of buildings. In particular, advances in metals, ceramics (including glass) and synthetic polymers have caused a virtual revolution in the nature of architectural assemblies over the past 75 years. These changes are noteworthy not only for the physical changes they have brought to contemporary architectural systems but also for the altered processes of production that are necessary in their application to buildings.

Contemporary glass and stone wall technologies are dependent on high performance sealants and adhesives. Multi-layered polymer coatings protect metals. Synthetic additives significantly augment the

performance of concrete. Contemporary buildings have been irrevocably affected by the innovations offered to architecture in these three materials classes. While a full rendering of the nature and extent of these innovations is not possible here, a sampling will provide a proper sense of the significance of these advances.

Material Advances

For example, aluminum was the first metal to be introduced into buildings since the late ancient period and it has now become second only to steel. In 1935, Le Corbusier wrote «The airplane is the symbol of the new age . . . The aluminum framework of an airplane —search for economy of material, for lightness, always the fundamental, the essential law of nature». (LeCorbusier 1935, 13) Aluminum is now produced in dozens of alloys and many extruded and cast forms. A recent invention is the production of a foamed aluminum for use in lightweight structural surfaces, Figure 5. Between 1910 and 1915 stainless steels were produced through the combination of iron and chromium. The use of stainless steels has significantly improved the durability of exterior envelope components. Entire façade assemblies have been made of stainless steel sheet; the Petronas Towers of Kula Lumpur being one recent example. Also, high performance fixtures for lighter glass walls are made using stainless steels, Figure 6.

Ceramics have been much improved in the last 100 years as well. These materials, classified into three groups —glasses, clay-based materials and cementitious mixtures— have existed for the duration of the making of building components. Most of the materials contained within the ceramics grouping contain silica (SiO_2). Portland cement, arrived at through a series of individual experiments by Smeaton, Parker, Frost, Aspdin and Johnson was patented in England by Joseph Aspdin in 1794, and used extensively in construction beginning in the early twentieth century (Moavenzadeh, 1990). Reinforced concrete was invented (1849) by Joseph Monier, who received a patent in 1867. It is important to note that Monier, a gardener by trade, was extremely important in continually inventing further applications and enhancements of reinforced concrete. Concrete now accounts for roughly 75% (by weight) of all construction materials used worldwide annually.

Recent improvements in concrete have been largely due to the range of additives, including synthetic polymers, silica fume and other pozzolans that have enhanced properties such as strength and ductility, decreased curing periods, decreased weight, improved durability and ease of workability. Fibrous reinforcing, both internal to the matrix and applied to the surface of the cured concrete has also improved its performance. In addition, cellular concrete has become a commonly used material in both block and panel forms. These new, higher strength and more durable concrete formulations are fueling a renaissance of cast architectural and civil forms, Figure 6.

Glass has been improved in a vast number of ways, from improved production techniques to the introduction of various methods for strengthening the

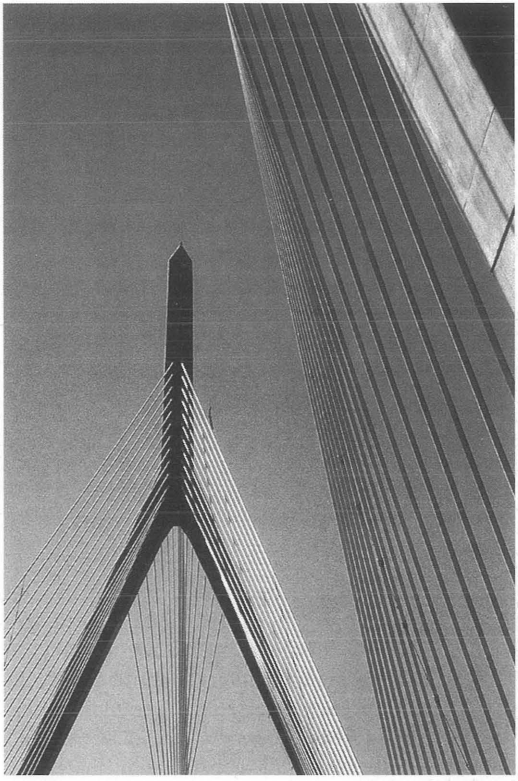


Figure 7
Leonard P. Zakim Bunker Hill Bridge, Boston, Massachusetts. Completed October 2002

pane itself to developing various forms of the material —fibers, silica foams and ultra-thin sheets. Glass coatings composed of thin metallic films have dramatically increased the thermal performance of insulated glass assemblies.

Synthetic polymers represent the clearest example of an entire subset of a materials class that was conceived of in the laboratory. In 1934, Wallace Carothers, director of research at Dupont, invented nylon 66. Since then polymer science has produced a virtual avalanche of synthetics polymers. Silicones and neoprenes, urethanes and EPDM, ETFE and many other synthetic polymers are used extensively in contemporary architectural assemblies. Polymer and engineered wood composites have been a subset of this field of research. Structural insulated panels, particle boards, polymer lumber and other types of cellulose reinforced materials have become a significant market of products, Figure 8.

These and many other examples illustrate the effect that the research laboratory has had on the physical components through which contemporary architecture is made. All of these material classes have been substantially altered through the work of a corporate research lab, sometimes in collaboration with an academic group and sometimes acting independently. As these materials are developed and placed in the marketplace they inevitably change the relationship between the contemporary designer and the building itself. «While the language of architecture and the nature of construction can never coincide, neither can they go their separate ways». (Ford 1996, 429) The plurality of architectural practice allows for a proliferation of forms and approaches to a point in which classification may seem impossible if not extremely difficult. The immense range between an architecture that acts as the simple resultant of technological forces and architectural form that productively captures innovation from other industries explains the diversity in building to be seen today.

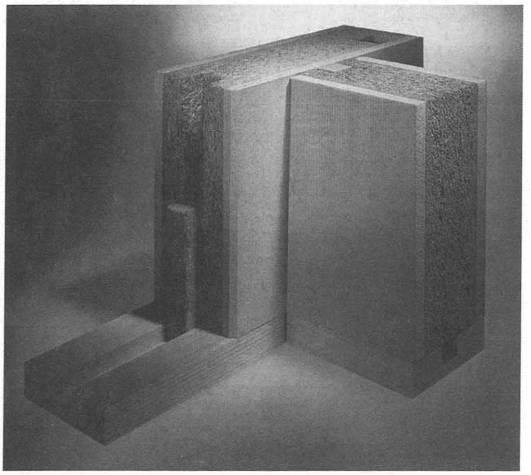


Figure 8
Wood and polymer composite wall panel

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Structure: Size, form and proportion. A historical review on the main criteria for structural design. Theoretical and empirical studies on dead load

José Luis Fernández Cabo

Thanks to progress made in analysis development, a great success has been achieved in the field of structural engineering.

Nevertheless, the aspects regarding the design of the preliminary schemes have been relegated, and even valid approaches have been abandoned in all this process. Our days, a key difference with regard to past times has been the introduction of computer-based analysis.

Traditionally, a common fact has conditioned the design of Architecture and Civil Engineering structures, namely, the little attention paid, and the difficulty, for getting industrial process. In Architecture spans have often been designed on a modest scale, and in Civil Engineering, even in larger spans, the designing process has not changed fundamentally over the last centuries. More particularly, the designer draws up some schemes, and then the structural type refinement is carried out slowly by combining analysis and practice.

In fact, the process works in financial terms, mainly due to the fact that optimization of the total cost either is not always equivalent to the optimization of the structure cost itself, or in case it is, it has been interpreted in the light of constructive —rather than structural— parameters.

This paper aims to provide a historical analysis on the criteria adopted in the structural design process. In this regard, the design will be assessed in terms of the quantity of material employed. Thus, the history of design process is in fact the dead load history. This paper will try to show that this has been the history of a conflict between theory and practice, a debate between two conceptions, the constructor's and the mathematician's.

HISTORICAL DEVELOPMENT

From the Ancient Structures to Galileo.

It is now widely accepted that the theory of structures first originated as a consequence of the Scientific Revolution. Galileo's *Discorsi* can be considered the first work in this field.

Architectural testimony from the previous centuries has been revealed to us more often through living facts than through first-hand written materials, which are in fact scanty.

In this respect, there seems to be no doubt as to the technical potential prior to the Scientific Revolution. However, there is no solid evidence as regards the existence of a substantial theoretical background at the time. Instead, those ancient projects might have been carried out following empirical knowledge.

Likewise, that empirical knowledge is sure to have adopted as a design instrument, explicitly or implicitly, the regulator alignments as well as the proportion rules.

The only factor common to all classicism stems from the use of the classical orders, and not from the adoption of a unitary system of proportion, which never existed. This fact was clear when the original art

works dating back to different periods were measured in the 19th century (Rondelet, 1834; Fauré, 1890).

Design empirical rules, most of them of proportional condition, have existed until the 17th century, with traces which get up to the first half of the 20th century. The empirical methods are really efficient when it is a slight variation in the shape and size of the structure, being used both premises till the 19th century.

The architectural type and the order allowed a correct and adequate structural design. That is encouraged by the confluence between structure and construction.

Galileo announced what we now know as cube-square law: given a body having any form and made of any material, if a change in size (L) is introduced (with the same proportions), the dead load increases in proportional to (L^3), while the resistant area increases in proportion to (L^2). Thus, we infer that:

a) geometric similitude does not imply, strictly speaking, mechanical similitude.
b) for any form and material there is a maximum size where the structure is only capable of withstanding its dead load.
c) maintaining the same form, proportion and material: stresses from the dead load ($\sigma_{\text{dead load}}$) increase in linear fashion as the size is increased ($\sigma_{\text{dead load}} \propto L$).

This argument refutes the use of both the architectural types and the proportional designing rules. In other words, it undermines the validity of the geometry as a design tool, and, in general, the face value often attributed to the analogical methods.

Nevertheless, the statement had no practical consequences. As a matter of fact, it can now be viewed as a fallacious argument, in so much as it does not have any effects on the intervals of size and materials widely employed in Architecture and Civil Engineering until the 19th century.

Regarding theory, the Scientific Revolution was liable for the acknowledgement of size as a structural problem, bringing forward a future controversy between Matter and Idea. For this reason, Panofsky gave Galileo the category of «an art critic» (Panofsky 1954).

From Galileo to the 1850s

The evolution of «the new science» was slow and gradual. First, the Academies and then the Technical Schools of Engineering started to gain foothold, but not much attention was paid to Galileo at the time. We will argue that the few authors who adopted and extended Galileo's theories soon fell into abeyance.

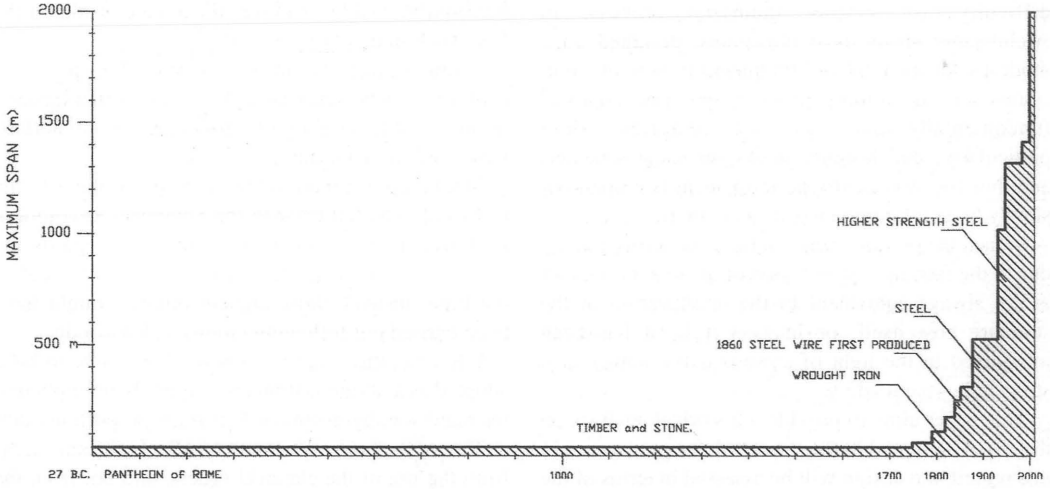


Figure 1
Drawing based on (Head 1988, p. 6) and enlarged by the author

However, an unprecedented increase in the structural spans took place at the turn of the 19th century. This process was to keep its upward trend until the second half of the 20th Century. Over the next one hundred years, the maximum sizes would be multiplied by more than 30. This is even more surprising now that we know the theoretical tools employed at the time.

The first big step ahead in spans —in the order of 6— took place in the first haft of the 19th century. By establishing the relation between the period and the size of the structures, we can easily understand why the 19th century has been regarded as a landmark in the history of dead load (Figure 1). Likewise, data show that this relation has grown exponentially since the first half of the 19th century.

For the first time, engineers were faced with dead load problems. Apart from an increase in size, the application of the new scientific methods resulted in higher proportional tensions (σ_i / σ_{max}) if compared to those considered in previous centuries.

Some highly illustrative data from these historical studies are worth mentioning now. In suspension bridges the range of spans was multiplied by five, and the relation of dead load and live load ($\wp_{dead\ load} / \wp_{live\ load}$) stood around 1,5 and 3 according to size in the period 1826–1883 (Steinman 1991). (See figure 4). 1883 represents the construction of the Brooklyn bridge in which the relation ($\wp_{dead\ load} / \wp_{live\ load}$) = 3.2. These excessive ratios, even for those spans, can only be understood in the light of very simple analysis patterns. The data collected by former authors show higher relationships (Rankine, 1863, p 583, Table VII).

However, for a long time Architecture remained unaware of this problem. Even the largest roofs did not exceed the limits of past construction based on masonry. The most frequent uses in Architecture proceed at a very slow pace, between 4–7 m. In this regard, any discussion on dead load runs the risk of turning out absurd. This situation was to change in the second half of the 20th century.

Dead load appeared in the theoretical field as far back as in the 18th century, but practical application did not take place until one century later, at least in great works.

But let us now review some of those theoretical works.

One of the earliest theoretical works was that of the American engineer, S. Wipple, who focused on the dead load optimization problem by means of differential calculus. He tried to gauge the optimal inclination of the truss diagonals so that the material employed is kept at a minimum. In this case, he used a model of single load, achieving an optimum geometry slenderness ratio (or just slenderness = span/height) up to six (Wipple, 1847). He was not absolutely right, but he was close.

The most outstanding figure in the first half of the 19th century was Rankine, who reformulated the cube-square law, and thence established an accurate and highly useful proportion. Expressing it in his original proportional notation, where (L) represents the size and ($\wp$) the load:[L_{max}:L:(L_{max}-L)::$\wp_{total}$: $\wp_{deadload}$:$\wp_{liveload}$]. To put in a different, and more simplistic, way: [$L_{max} / \wp_{pp}$]=[(L_{max}-L) / $\wp_{ext}$]. (See figure 2). (Safety factors have been omitted).

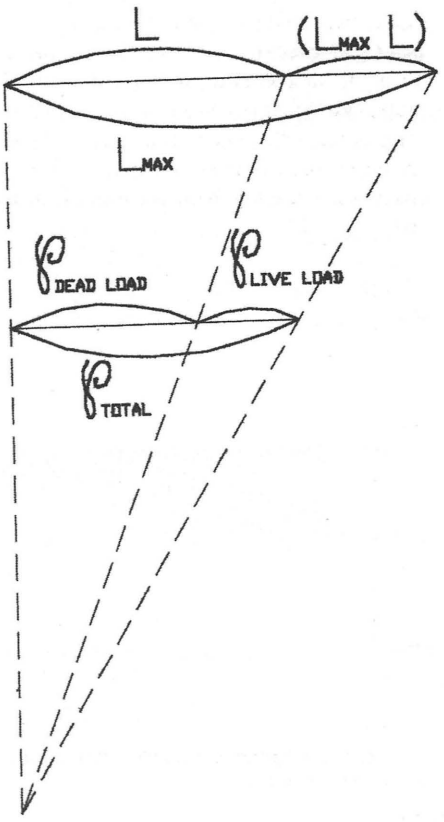


Figure 2

The notation allowed him to calculate the maximum size of different structural types of bridges from dead load data available. Now, we will take a closer look at one of his definitions of structural types «Warren girder bridges, not continuous, with cast iron struts, depth about 1–15th of the span» (Rankine, 1863). On defining Warren's type and slenderness in the order of 15 he is defining geometry already, even though his statements are not so precise in other cases. This structural type gradually reduced its slenderness by half in a short time following a semi-empirical process. On a general basis, later authors did not consider the slenderness criterion, as it was implicit in construction practice.

Rankine can be said to be one of the very few theorists of 19th century to be aware of the direct relation between slenderness (λ=span/depth) (he would always speak of the relation «depth to span») and the structure stiffness. As a matter of fact, in the case of simple beams with constant section, he established a method of sizing stiffness by means of this parameter. This one has been proposed, independently, by Prof. Ricardo Aroca.

Additionally, Rankine introduced a variable that was to be central to the dead load debate, namely, the relation (σ/ρ), that he termed «Moduli of Stiffness and Strength.» (Rankine 1863, pp. 230, art. 154). He identified its physical sense too, the greatest size a prism of constant section may achieve (disregarding the stability problems). This parameter appears when the greatest size is established by means of the strength of a simple beam of rectangular section subjected to his dead load.

Rankine's work was at once brilliant and isolated. Moreover, he enjoyed widespread recognition, but his dead load and design works were not fully understood, maybe because they might have been at odds with the time.

Despite the fact there was not a general theory of design in the first half of the 19th century, and well into the 20th century, the most outstanding progress made in the design of structural types took place at that time. For the first time, we could now affirm that the working of structures has been scientificly understood.

The introduction of steel as a new material, that engineers used far from any previous formal preconception, would undoubtedly contribute to the development of new structural types. The triangular structure is born at the same time as steel. The previous works in wood were limited and generally hybrid. Perhaps, the only pure case is that of Palladio's.

On a general basis, in wood structures up to the 19th century, the triangulation is an element employed to stabilize a general arch mechanism (see figure 3).

The layout of simple triangulation, at least initially, is closely linked to the necessity of designing determined structures. In fact, there are many examples of steel and wood trusses dating back to the turn of the 20th century most of which were not effectively. This show the absence of the theory of designing. Slowly,

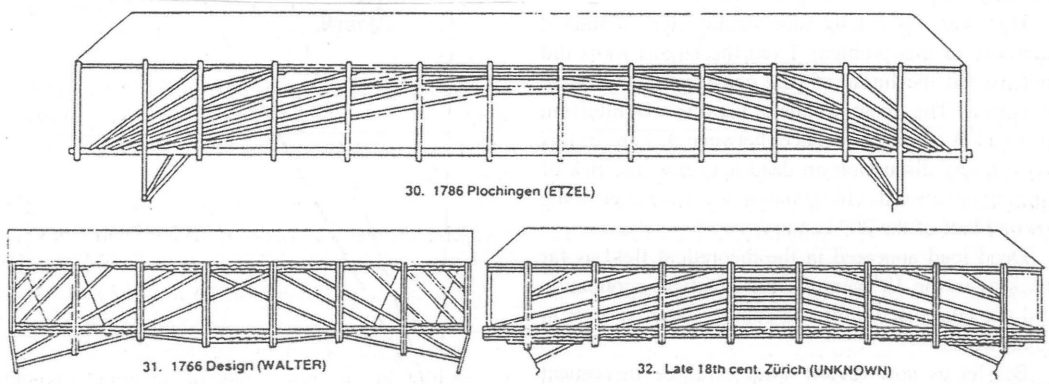


Figure 3
Wood trusses from different periods, where structure variation of internal configuration can be observed. (Taken from James, 1982).

and when the problem has been progressively understood, and chiefly due to a «selective natural» process, many of those structural types have fallen into oblivion. By the mid 20th century, simple truss types did not exceed three or four.

From 1850s to 1950s

Even though the 19th century witnessed the establishment of some analytical bases in the field, a full-fledged theory on designing was never developed. The understanding of the structure was up to the simple structural analysis and design, although little was known about how to improve the efficiency of the structure geometry. Thus, there was not other way but using a combination of analogical methods and trial and error processes.

We have previously referred to trusses as a paradigmatic example of the changes taking place in this period. Waddell's book gathers 34 structural types of simple truss bridges (Waddell 1916, Chapter XXII). Among all these schemes, some of this are not as efficient as one could expect, since they had triangulation patterns far from 45 °. Not only were they poor, but they were virtually equivalent in terms of the employment of materials. In view of the above, we can infer that the geometric variables allowing optimization of trusses were generally ignored at the time. By the end of the 19th century this situation was to change; some studies from the beginning of the 20th century already found the main criteria to be applied in truss design.

From the mid 19th century, and once the importance of size was fully recognized, a lot of theoretical and, mostly, empirical work began to expand.

During this period spans continued growing. By the mid 19th century, Bessemer converters allowed mass producing steel at a lower cost. «Prior to 1840, most of the evolution of bridge construction in the United States was along the lines of the wooden truss and the wooden arch». (Waddell, 1916: 1–19). In this same period., the development of railways and the introduction of the gas motor represented a great contribution to the process. The number of cars in the United Stated between 1900 and 1940 soared from two million to thirty million. However, not only the greater spans were still produced, but also smaller-scope ones topped all prior production. It is not coincidental that most empirical data of the period have been collected in the USA. Given the high amount of structures built in this country, it has been possible to focus the problem of the dead load determination from an empirical perspective.

But the theoretical studies were inescapable at this time. We will now proceed to outline some of those studies before passing on to the empirical section.

There was a large group intent on optimizing the simple truss design, mostly the one employed in bridges. We could say they followed Wipple's approach. The main objective was to determine the optimum depth.

In 1871, T. Willis Pratt threw some discussions about the economy of the sample truss. In 1877, Emil Adler set up a model for the determination of the optimum depth, with wrought iron, and for a truss of parallel chords: $\wp_{chords} = \wp_{struts} + \wp_{diagonals} \cos(180–2\alpha)$; being ($\alpha$) the angle formed by the diagonals with the horizontal plane. This expression is not correct, but it is obvious that the optimal results are reached with angles near 45°.

That same approach was adopted ten years later by John Lundie and Sherzer, who made the following remarks: first, the formula does not consider the influence of the bar buckling, and second, the optimum depth established for a simple panel cannot be applied to the rest of the truss. At the turn of the 20th century, Waling affirmed that in case this formula was taken as valid, then it would demand a trial and error test-case.

In 1877, Charles E. Emery developed another trial and error model in order to calculate proportions of the minimum load in parallel chord trusses. He based his work on big depths, except in the case of grids, twice as large as the ones previously in use. In fact, what W.E. Searles did in 1878 was using Emery's conclusions successfully so as to restore a wooden truss of parallel chords.

In 1887, A.J. Dubois proposed some complex formulae on the evaluation of bridge dead loads and economic slenderness of iron trusses with parallel chords. He is also known for developed formulae for masonry arch sizing. The empirical formulae for arch sizing had a long-standing tradition that would leave an imprint in the most relevant technical manuals until the second half of the 20th century.

As we have affirmed, these studies do not focus the problem, since they do not offer mistaken results. As

it is often the case with empirical research, practice is always ahead of theory. If we observe the design of the simple trusses, most of them show good geometrical desings: diagonals with angles in the order of 45° and slenderness between 6 and 8. Being these the two important variables. It seems clear that, in spite of the theoretical scarcity, some highly interesting projects were designed at the time.

The most important theoretical progress took place with the new century, but recognition would come much later.

At the end of the century, Maxwell developed a theorem that was to be central to the establishment of a design theory of structures. The new theorem would allow measuring the efficiency of geometry (Maxwell, 1890). Soon afterwards, Mitchell supplemented Maxwell's work with two theorems essential to understanding the optimal geometry (Mitchell, 1904). Mitchell's theorem based on Maxwell's expression, estates that, given a load system (N = axial force; L = bar length): $(\Sigma N_i L_i)_{\text{COMPRESSION}} - (\Sigma N_i L_i)_{\text{TENSION}} = K$; $//K$ remains constant. Michell proves that the structure involving less quantity of material is also the most stiff, and also that in the case of structures with compression and tension groups, and for any optimum, its meeting takes place at 90°. In fact, this is tantamount to establishing the differential equation of the optimal geometry. Given the abstract nature of the concept, engineers of the time might have been unable to grasp its full implications.

Among the theoretical approaches there is a fraction that applied the new theories of dimensional analysis to the structures field.

Most of these authors only provide conclusions too general in scope, among them we can mention Archibald Barr, James Thomson or A. G. Greenhill.

One of the most interesting works belongs to Lord Rayleigh (1915). Given similar structures, the dimensional variables are: stress, size and forces. The non-dimensional variables gather in factor $\varphi()$, which comprises topology; proportion; sizing and the relative distribution of loads. The problem is defined with only one non-dimensional monomial $[\sigma L^2 / \wp]$ usually expressed by stating the normal stress: $\sigma = \wp \varphi()/L^2$. In the case of dead load where the load is sort $\wp = \wp\ (L^3)$; it is easy to obtain the relation of stresses already stated by Galileo and Rankine: $\sigma_{pp} = kL$ where (k) remains constant.

In 1888, the Spanish engineer Joaquín Pano Ruata published some articles on the prediction of dead load and size limits. There is unanimous agreement in the literature as to the quality of this work as unique in the Spanish 19th century context. He set up a manageable dimensional study with the tools first employed by Galileo or Rankine . By re-elaborating the formulae, we come to the same conclusion as Rankine's: $[L_{max} / \wp_{pp}] = [(L_{max} - L) / \wp_{ext}]$. The next step is also similar to Rankine's. Based on data from structures in existence, he reached the maximum sizes for different types. Pano's formulation seems more comprehensive than Rankine's. Moreover, the variables used are not the same, so that a common theoretical core is hard to maintain. In view of the above, we could assume that none of them had any influence among their contemporaries. Yet, it is even more surprising that, in Spain, Eugenio Ribera's Encyclopaedia does not include any mention.

However, dimensional analysis could not go further from Rayleigh's work, though its consequences may not have been really exploited. At first, dimensional analysis could not establish the variables of the problem, but it allowed to establish its dimensional relation once the variables were given. Since the key problem was to know these variables, this procedure was not to be successful.

Additionally, Rayleigh chose a correct number of dimensional variables in order to solve the problem accurately with regard to dimensional analysis, yet the variables of the problem of dead load were not defined in any way. The shape factor $\varphi()$ comprised all the geometrical variables of the problem without defining the parameters they depended on. This procedure only succeeded with reduced samples.

At the end of the century, the first published critics on the theoretical approaches for the determination of dead load began to emerge (Waddell 1896). As previously referred, from the first half of the 19th century an exponential increase in all known built structural types took place; thus, the empirical practice could improve. This was without doubt a pragmatic, brief solution. On the other hand, technicians did not establish theories, but set bounds to problems with the known theories. Likewise, it is understandable why the development of the theory was scarce.

Waddell not only was a North American engineer of great experience, but a firm. In his book of 1916

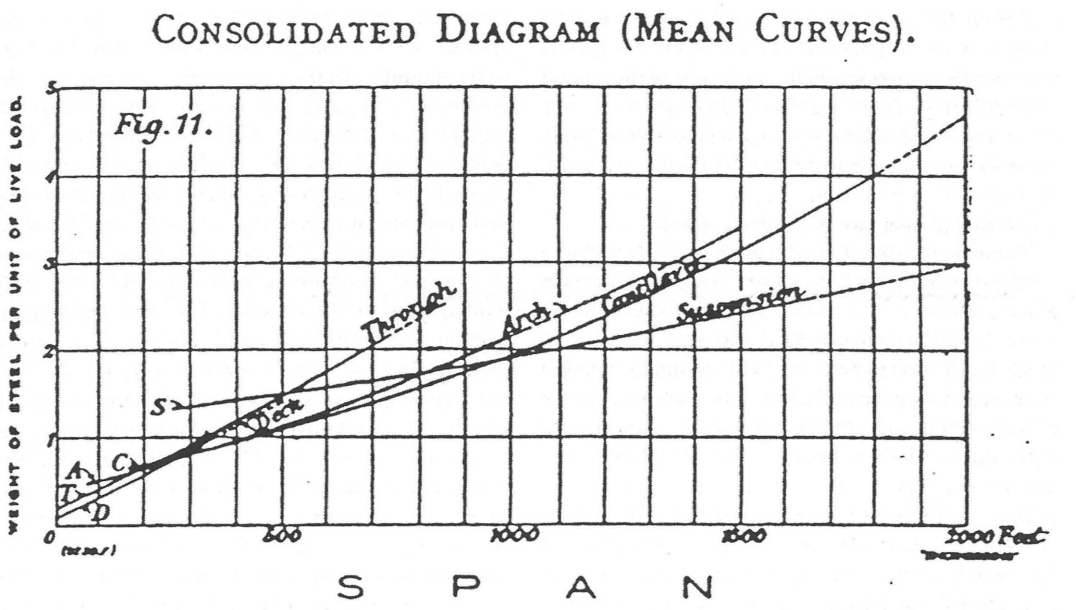


Figure 4
Relation between ($\wp_{\text{dead load}} / \wp_{\text{external load}}$) and the size for different steel bridges. (Thorpe principles of the 20th century).

about bridges construction we can find also the state of art regarding bridges design. (Waddell 1916, 1; Chapter XV, Principles of Designing). The title of the chapter cannot be more promising. Let us now have a look at some of its principles. «Principle I: Simplicity is One of the Highest Attributes of Good Designing». »Principle II: The Easiest Way's the Best». «Principle V: There are No Bridge Specifications Yet Written, and there Probably Never Will be Any, which will Enable an Engineer to Make a Complete Design for an Important Bridge without Using His Judgment to Settle Many Points which the Specifications Do Not thoroughly Cover; or as Theodore Cooper Puts It:- The most Perfect System of Rules to Insure Success Must be Interpreted upon the Broad Grounds of Professional Intelligence and Common Sense-» Principle XLIX: The Science of Bridge Designing Lies Mainly in the Detailing».

Waddell established 50 principles which showed deep *savoir faire* in the subject. Though, these principles have been implicitly used for centuries, they had little in common with a general theory of design. This theory was not based on the scientific knowledge, but on practice, something that already existed before the Scientific Revolution.

Due to the complexity of the problem, Waddell opted for empirical approximations, though his works were too theoretical. He not only carried out a great amount of work on empirical formula of dead load, but he also established his proposals to modify those expressions when some of the variables changed. In order to do this, an understanding of variables was required. Both, the variable of the material and its linear influence were perfectly identified, but this was not same for the geometrical variables. Waddle stated dimensional analysis reasoning in order to quantify the influence of the depth, in the case of trusses of parallel chords. It is somehow paradoxical that one of the greatest enemies of the theoretical approach was not aware of the major advances he was giving in his effort to manipulate the empirical approach. The problem was that they did not know how to propose a change in geometry in a more general way. Thus, as this empirical work was too specific, and other manipulations required of a theoretical knowledge which did not exist at that moment; all this work fell into oblivion.

One of the most complete compilations in steel bridges, was that carried out by W.H. Thorpe. It seems obvious that Waddell's work was more general when trying to propose methods in order to modify the empirical formula. From my point of view, he is conscious of the great limitations of the empirical approach.

Let us look into one of Thorpe's graphs.

In practical terms, at least temporarily, the problem is solved by applying this method. Another key aspect of the problem is also shown, namely, the essentially linear variation between load and size recorded in practice. However, there are still too many implicit geometrical variables which do not contribute to the understanding of the problem. Likewise, these are the most outstanding geometrical variables regarding design.

New attempts to apply the dimensional analysis and combine both the theoretical and the practical approach were then carried out. In an effort to apply this method, Steinman (1911) tried to solve in a rational way the maximum sizes as well as the economic intervals of different structural types. He centered his work in cantilever and suspension bridges, as they were the only types used in great spans. More particularly, he worked on what he named general semi-empirical formulae, in function of constants (which comprise form and material) from reasoning of similar dimensional analysis to the ones used by Galileo. In order to determine those coefficients he used theoretical calculus instead of using the available empirical data. Thus, his proposal did not succeed, and Waddell disagreed about the existing empirical data.

Shedd's work was one of the most interesting ones regarding to design process. Like Steinman, he combined the theoretical and the practical approach, giving formulae for the optimum depth of bridge girders. He established a dead load empirical formula for railway bridges: $[\wp_{pp}/L^2] = CL(\wp_{ext}/L^2)/\sigma$. Where parameter C is a constant which remains almost invariable respect to size; increasing in small spans in order to correct the dimensioned excess. With regard to trusses, he established a limitation of triangulation angles with the horizontal between 45 and 60°, the optimum being between 50 and 55°. Though practice had assumed these essential problems long time ago, they are not clearly shown nowadays.

It is obvious, that most of the graphics and formulae were made for bridges. In the 1930s a great number of formulations were settled. In USA there were multiple works as unified codes were not established till after the Second War World. M. Ketchum's (1914, 1921, 1924), F. Dufour's & P.C. Schantz's (1931) or T. Shedd's (1934) manuals showed a broad range of formulae and graphics. The first ones are of type: $(\wp_{pp} / L) = C_1 + C_2L$; being C_i = constants which depend on the shape, on the kind of live load (in those years bridge load types were typified) and on the material. The next step was the introduction of the width bridge (b) as a variable:$(\wp\subset_{pp} / L) = C_1 + C_2b + C_3L + C_4bL$. The last step was to correct the small linearity deflection which is produced with the size increase: $(\wp_{pp} / L) = C_1 + C_2b + C_3L + C_4bL[1 + C_5L]$. The dependent variable is the dead load for unit of length. This is right, as the live load for unit of length is a constant datum in this problem, at least for big sizes. From the relation $[L_{max} / \wp_{pp}] = [(L_{max}–L) / \wp_{ext}]$ it may be observed that in built structures, the relation is basically linear as empirical formulae indicate.

Empirical formulae also appeared in Architecture structures field especially in roofs, even though in a decreasing degree. Robins Fleming gathered 13 empirical expressions for the dead load calculus of roof trusses (Fleming, 1919). After analyzing these expressions, he reached two successful conclusions.

His first conclusion was that between such formulae there were some times very great differences. He marked out that the variables were not always the same as they were not clarified. Such formulae were very restrictive due to the chosen variables and they were to be used cautiously.

With regard to his second conclusion, dead load had an influence not greater to 15%, due to analyzed structures size with spans between 15 and 30 m. According to Fleming it was of no need to proceed any further.

At the beginning of the 20th century, concrete was used in construction works when structural types creativity was not decreasing yet. In fact, working with concrete was parallel to shells development. Soon concrete will compete with steel in most samples. At this time, different empirical formulae for bridges and roofs were also used.

On the other hand, high-rise buildings arose in architecture between the turn of the 19th century and the beginning of the 20th in USA. Some of the most

well-known being: the Monadnock building (1890–91) in Chicago having 16 stories, the Woolworth building (1911–13) in New York with 50 stories. The Empire State (1929–31) with a total height of 373m and an unfit structural design. Thanks to Goldsmith and F. Khan this type of constructions is to be improved in the 60s and 70s.

From 1950s to the XXI century

There was a continuous decreasing of structural types from mid 20th century. From the mechanical point of view, despite the fact many more constructions were carried out in this period than in previous times, the greater structural types development arose basically in high-rise buildings, above all in the tension roof structures field.

In that period, bridges design proceeded with its even slower improvement of semi-empirical kind inherited from the 20th century. Comparing the suspended bridge over the Mena, of Telford (1825), which has a span of 177 m, and the Akashi Kaikyo (1996), with 1990m of span, there is only a notable geometric difference, that is to say, slenderness goes from about 14 to 7. The topological configuration and the method of the initial design proposition has changed very little, and it certainly may be improved.

Meanwhile, the frequently empirical formulation nearly disappeared. Though, there were some reminders, such as, the ACI that offered a general linear formula to determine the total dead load for unit of surface of six different types of concrete bridges (ACI, 1992, 343R–58). The interval size for every type was offered but not its slenderness; namely, the same as was done in the beginning of the 20th century formulae. Slenderness, as we have previously said, is actually an implicit datum. We must wonder here, the reason of the key parameters implicitness.

However, the only group of experts who considered empirical formulation essential, in the mid 20th century, was started by Myron Goldsmith in the IIT of Chicago (Goldsmith, 1953). Fazlur Khan was to join it soon afterwards. Goldsmith monitored several Ph. Doctorate research works in the 60s, among which we can mention David Sharpe's, Phyllis Lambert's and Peter Pran's. Those studies including data from concrete and steel roofs are still applicable. In most North American bibliography produced by this group of authors, there is not a single reference to the empirical formulae for the design of bridges dating back to the beginning of the century. These formulae show the same conclusions as the ones achieved in the case of bridges: the load variation for unit of surface with relation to size, is essentially linear; when this variation is not linear, the structural type is not considered for this size and it will be necessary to change the form, to change the type.

Goldsmith was the first person to realize that the existing structural types in high-rise buildings with small spans gantries did not bear any relation to great sizes. Instead, he proposed a very interesting high-rise building which laid the basis of Fazlur Khan's future work.

Following Goldsmith work, Fazlur Khan was the main thinking-mind behind the typological evolution of high-rise buildings. Between the 60s and 70s high-rise buildings achieved appropriate structural types thanks to Khan. However, the new structural types stemmed from an empirical, rather than a theoretical, process. The new methodology yielded excellent results as previously in bridge design. Moreover, design efficient rules were also generated (Iyengar, 1979), namely, reasonable size limit is defined by the relationship: $\wp_{\text{horizontal load}} \leq \wp_{\text{total loads}}\ 0{,}35$.

In this period, which was to witness the establishment of the optimization theory, authors as Hemp, Prager, Cox and others resumed and enlarged Maxwell's and Michell's work. Then, linear programming procedures began to be applied. Nowadays, nonlinear optimization methods are fully consolidated.

Until the present moment, the field of application has been carried out on those works where an industrialized production exists. However, its application to Civil Engineering is much more recent. As we have previously mentioned , without an adequate repetition, the variable which determines financial optimization is not always the quantity of material.

In Architecture structures field, most tensioned structures are mechanisms, thus the initial way they should be presented cannot be arbitrarily chosen. It is easy to make a preliminary design which may determine the structural type, but without establishing a precise geometry. The exact geometry definition

requires sophisticated process, where for the first time the structure geometry is to be the output. Actually, there has been no change in the design general approach. Previously, the form, and even the sizing, is basically established thus, we cannot infer it is really an «output».

From my point of view Prof. Ricardo Aroca's work has been essential clarifying the fundamental variables of the dead load problem in the second half of the 20th century. His approach is based on authors such as Rankine's, Mazwell's and Michell's, though a great advance is to arise in the geometric variable. This work is to define the main variables of the dead load problem for the first time: size (L), geometry (K), proportion (λ = span/depth) and the material (σ/ρ). Prof. Ricardo Aroca not only emphasizes the great influence of geometry, but he also demonstrates that the essential parameter is slenderness (λ).

Under these variables, dead load is defined by: $\wp_{\text{dead load}} = \wp_{\text{total}}\ L\ K\ (\rho/\sigma)(1/2)(\lambda/\lambda_o + \lambda_o/\lambda)$; being ($\lambda_o$) the optimum slenderness. For maximum size, the total load is only the dead load, thus maximum size is explained only in terms of material (ρ/σ) , geometry and proportion: $L_{\max} = 1/[K\ (\rho/\sigma)(1/2)(\lambda/\lambda_o + \lambda_o/\lambda)]$. This is a theoretical maximum. Real maximum sizes are about 20% of the theoretical ones. Structure stiffness may be also expressed by means of these variables.

The understanding of the problem as well as the consideration of its variables, allows predicting whether a geometry is mechanically acceptable at a first glance, which provides a first-rate designing tool. In fact, this approach demonstrates the face validity of the structural type as a designing tool. Basic geometry includes the main variables to control mechanical efficiency. Thus, analogical methods success is based on its application.

This relation between geometry and size is assumed too soon in the engineering practice. But, usually , there has been a tendency to ignore the importance of geometry in mechanical efficiency. This may be influenced to the fact that geometry is always part of the input in the usual analysis process.

Some ideas about the XXI century

Nowadays, optimization algorithms have achieved an outstanding development. In highly defined problems, geometry itself is the output. The drawback of these methods is its numerical condition as it does not help in the understanding of the problem nature.

The customary practice has not taken into consideration these new approaches, and the working method, referred to design process, has not been modified for ages. The main unquestionable tool continues to be the structural type, and the analogical is the method used. Likewise, the new tools blaze an unprecedented trail in the history of structures design.

On the other hand, the numerical algorithm works out with very specific conditions and its reprogramming can be very difficult. Practically, it is not easy to establish which are the key parameters to be optimized, even referred to cost. Besides, the structure cost is usually a small part in the problem. As far as now, I agree with Waddell and Cooper that the best computer to face these questions is our mind. Structural types are valuable tools though their use requires a non verbal education and experience.

In structures of great size, or in those which will be repeated many times, traditional methods would not surely be so efficiently. Every problem requires its own different tools; and as there is no sense to establish abstract comparisons, neither is to fix to known procedures as a unique way of proceeding.

On the other hand, all prior empirical and theoretical advance of olden times on dead load and structural design is still a great uncharted area. Surely, computer use has some say in the whole process; in truth, there is always the downside to every innovation.

This century should step ahead in the development of design tools, of which the computer is only one instrument among many more.

Conclusions

1. Design tools have not been up the same development as those applied to analysis. In turn, most of the achievements in analysis have also been parallel to lost of the already existing designs tools.

2. There is a great number of theoretical and empirical tools, though they are mostly scattered and often unavailable.

3. Structural types have been and still are the main criterion for structures general design. Furthermore, they constitute the core of the analogical method, in

so much as they go beyond the limits of geometry and materials.

4. The basic geometric scheme reveals important information about the mechanical behavior of structures. Given a fixed material, the geometry is the main variable in design, being slenderness the key point. This fact backs up the use of this basic geometry as a design tool.

5. There is now an increasing controversy about the use of geometry as «input « for some of the design problems outlined in this paper. In the short term, software developments will lead to a new approach to the structure design problem that should combine both the traditional perspective premised on shape and a more recent one in which form represents the result instead of the onset datum. This fact stands up in clear contrast to current trends in architectural training, so that any progress in the field is bound to overcome these monolithic practices.

6. The absence of a general design theory has not prevented the development and evolution of structural types. This process has combined both logic and analogical methods, sometimes unconsciously. In fact, the establishment of a general design theory is not an indispensable condition, yet it can put an sort-cut on the design processes. Likewise, the non-linear iterative condition is peculiar to design itself. Thus, the evolution of the process seems more important than the onset data.

7. This historical research has done nothing but proving Thomas Khun's theory in that «Perhaps science does not develop by the accumulation of individual discoveries and inventions.» (Kuhn, 1962: 2). Maybe, we are now on the verge of witnessing the revolution of structural design process.

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The masonry arch between «limit» and «elastic» analysis. A critical re-examination of Durand-Claye's method

Federico Foce
Danila Aita

The historical evolution of the theory of the masonry arch is marked by two alternative structural philosophies corresponding to what we modernly call «limit» and «elastic» analysis.

According to the first approach, global *stability* is the main question and the safety of the arch is guaranteed if *any* equilibrium condition preventing rigid mechanisms exists. This is the *equilibrium* approach followed in the first 18th century studies on the masonry arch and successfully developed in the first half of the 19th century on the basis of Coulomb's method of maxima and minima.

According to the second approach, local *stress* becomes the object of investigation and the safety of the arch is assured if *actual* stresses at each cross section are below the admissible strength of materials. This approach, which necessarily involves the complete set of *equilibrium*, *compatibility* and *stress-strain* equations, was the unavoidable result of the developments of structural mechanics starting from the twenties of the 19th century, when «elasticity» and «strength» became the new passwords of the theoretical research.

Nevertheless, the alternative between limit and elastic structural philosophies —*stability* versus *stress*— is not so radical as it may seem at first sight (Foce and Sinopoli 2001). As a matter of fact, it can be rationally removed by following an intermediate approach proposed by the French scholar Alfred Durand-Claye in 1867. This approach aims at verifying, as the author wrote, «s'il existe des solutions d'équilibre compatibles avec un effort-limite donné». This methodology preserves the non-deterministic character of the limit analysis and, at the same time, embodies the main aspect of the elastic analysis by imposing a restriction on the stress level.

The Theory of the Masonry Arch in the Tradition of Limit Analysis

Aiming at discussing Durand-Claye's contribution between limit and elastic analysis, it is reasonable to provide a brief account of the main steps of the vault theory «before» and «after» it. The method proposed by the French scholar represents, in fact, the only rational procedure for conciliating the spirit of the limit approach with the new instances of the *Résistance des matériaux*. History shows that, before Durand-Claye's contribution, any attempt of introducing the basic aspect of strength within the logic of collapse analysis resulted in fallacious procedures; on the other side, after it the uncontested success of the elastic methods of structural mechanics hid the profound sense of the limit approach applied to masonry vaulted structures, imposing the illusory research of the «unique» solution.

As known, the limit analysis of rigid systems represents the way followed from the beginning of the mechanical research on the masonry arch. For the

time —we are speaking of the first 18th century studies on the subject— it was certainly the only possible, as it requires nothing but the laws of equilibrium. No matter of stress, strain and actual strength enters the problem of the arch, nor could it be otherwise. As asserted by Coulomb following Bossut, masonry is «composé de fibres roides, ou qui ne sont susceptibles ni de compression, ni d'alongement» (Coulomb 1773, 351). In short, the masonry arch is seen as an assemblage of rigid and infinitely resistant voussoirs subject to the constraint of impenetrability and to the friction resistance (cohesion of the mortar, if present, is usually considered as negligible). If the equilibrium of such an assemblage is impossible, this means that the voussoirs will take some relative movements which transform the arch into a mechanism. These movements may be both rotations around the edge of the joints or slidings along the surface of the joints. By properly combining rotations and slidings at different joints the complete spectre of the collapse modes can be derived. The main purpose of limit analysis is exactly to assure that, for an arch of given geometry, load and friction coefficient, no collapse mechanism can occur.

For at least one hundred and fifty years theoretical investigation dealt with the analysis of the collapse mechanisms and the consequent design of the structural elements (thickness of the arch, size of the piers etc.). Initially, this investigation was developed on the base of simplified or arbitrarious hypotheses about the location of the rupture joints, the types of collapse mechanisms, the role of friction. The so-called «wedge theory» formulated by La Hire in 1712 is probably the first example of this type.

From a theoretical point of view, however, a real improvement of the limit analysis may be found only in the well-known *Essai* by Coulomb (1773). The method of maxima and minima, introduced by Coulomb together with a rational way of quantifying the role of friction, makes the complete discussion of the collapse modes of a symmetric arch in terms of statically admissible thrusts possible. The conditions of stable equilibrium can then be expressed by disequalities between the extreme values of the crown thrust which prevent the rotational and translational movements of a voussoir.

To tell the truth, Coulomb did not fully develop his method, as he failed to analyse all the possible rotations of a voussoir in relation to the application point of the thrust at the extrados and intrados of the crown joint. As recently shown (Foce 2002), the general treatment of the problem was given by Persy in 1825 and Navier in 1826, almost fifty years after Coulomb, and the complete discussion of the eight collapse modes of a symmetric arch was given by Michon in 1857.

The theoretical contribution of these authors can be summarized as follows. For a symmetric arch, let's consider the limit equilibrium of a generic voussoir —subtended by the angle θ and subject to its own weight $W(\theta)$ and the horizontal crown thrust (Figure 1)— with respect to the four rigid movements of downwards sliding, upwards sliding, rotation around the intrados edge, rotation around the extrados edge. The corresponding values of the thrust are:

for the downwards sliding $A = W/\tan(\varphi + \theta)$
for the upwards sliding $A_1 = W/\tan(\varphi - \theta)$
for rotation around the intrados edge $B = W\, x_i/y_i$
for rotation around the extrados edge $B_1 = W\, x_e/y_e$

where φ is the friction angle and x_i, x_e, y_i, y_e are the lever arms of weight and thrust from the intrados and extrados edges.

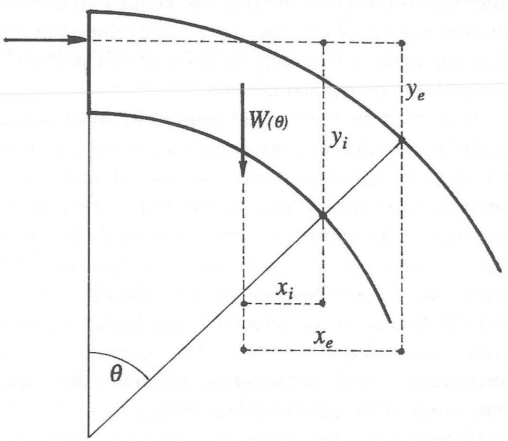


Figure 1

According to the method of maxima and minima, with respect to θ the greatest values of the thrust corresponding to the inwards movements of the

voussoir —that is $max(A)$ and $max(B)$— and the smallest values corresponding to the outwards movements —that is $min(A_1)$ and $min(B_1)$— must be determined. Moreover, for the geometrical compatibility in the case of mechanisms with relative rotation at the crown joint, the thrust must be applied at the extrados or the intrados of the crown. Thus, conserving the notations $max(B)$ and $min(B_1)$ when the thrust is applied at the crown extrados, the new notations $max(b)$ and $min(b_1)$ must be introduced when it is applied at the crown intrados.

The six extreme values of the thrust —$max(A)$, $max(B)$, $max(b)$, $min(A_1)$, $min(B_1)$ and $min(b_1)$— are associated with the six rupture joints $[A]$, $[B]$, $[b]$, $[A_1]$, $[B_1]$ and $[b_1]$. The relative location of the rupture joints makes it possible to deduce the complete spectre of the collapse mechanisms. As shown by Persy, Navier and Michon, there are eight collapse modes for a symmetric arch (Figure 2). According to the method of maxima and minima, none of them can occur if $max(A, B) < min(A_1, B_1)$ for thrust applied at the crown extrados, and $max(A, b) < min(A_1, b_1)$ for thrust applied at the crown intrados. Equilibrium becomes unstable —so that collapse can occur— when one of the following conditions is fulfilled:

I mode	$max(B) = min(B_1)$	with $[B]$ over $[B_1]$
II mode	$max(b) = min(b_1)$	with $[b]$ under $[b_1]$
III mode	$max(B) = min(A_1)$	with $[B]$ over $[A_1]$
IV mode	$max(B) = min(A_1)$	with $[B]$ under $[A_1]$
V mode	$max(A) = min(A_1)$	with $[A]$ over $[A_1]$
VI mode	$max(A) = min(A_1)$	with $[A]$ under $[A_1]$
VII mode	$max(A) = min(b_1)$	with $[A]$ over $[b_1]$
VIII mode	$max(A) = min(b_1)$	with $[A]$ under $[b_1]$

Elasticity and Strength: New Passwords of 19th Century Theoretical Research

The years of Persy, Navier and Michon's fundamental works are very significative not only for the theory of the masonry arch but also as they correspond to the period during which the theories of elasticity and strength of materials were being scientifically formalised. In the twenties Navier himself, Cauchy and Poisson laid the foundation of the general theory of the elastic bodies, followed some years later by Lamé, Clapeyron and Saint-Venant. In 1852 Lamé published his *Leçons* on the mathematical theory of elasticity, the first comprehensive book on the subject; in 1855 Saint-Venant completed his fundamental memoirs on the elastic flexure and torsion of beams.

During this revolutionary development of structural mechanics in the name of «elasticity» and «strength», the research on the masonry arch followed its own way, in confirmation of the persistent distinction between construction *en charpente* and construction *en maçonnerie*. Persy's *Cours* and Navier's *Résumé* are good examples of this state of things. Both the treatises are mainly devoted to the new themes of the *Résistance des matériaux* and contain separate sections dealing with the stability of masonry arches and retaining walls in the tradition of limit analysis.

Nevertheless, the signs of the new times were becoming more and more manifest. It is not by chance that the first clear hint towards the elastic interpretation of the masonry arch may be found in the same *Résumé des Leçons* by Navier. As we have seen, this book contains the correct discussion of the stability conditions on the base of Coulomb's method. After this discussion, however, Navier takes into account the actual strength of masonry and suggests an apparently small revision of the results of limit analysis. Examining the first rotational collapse mode, for instance, he interpretes the opening at the rupture joints as the incipient cracking corresponding to the triangular stress distribution on the joint surface. This interpretation is of little consequence in quantitative terms, as it provides a slight variation of the extreme values of the crown thrusts calculated in accordance with the collapse approach. It represents, however, a radical turn from a qualitative point of view. Navier's idea, in fact, is declared in the statement that,

> les voussoirs n'étant pas des corps parfaitement durs, on ne peut admettre que les pressions s'exercent ainsi contre des arêtes. Cela n'empêche pas que l'on ne puisse calculer, avec une exactitude suffisante, l'équilibre des voûtes d'après les règles énoncées précédemment; mais il paraît nécessaire d'avoi égard à l'élasticité de la matière des voussoirs . . . Cette question serait un cas particulier d'une question plus générale, qui consiste à déterminer les effets qui se produisent dans un corps élastique de figure quelconque, soumis à l'action de diverses forces. (Navier 1826, 164–165)

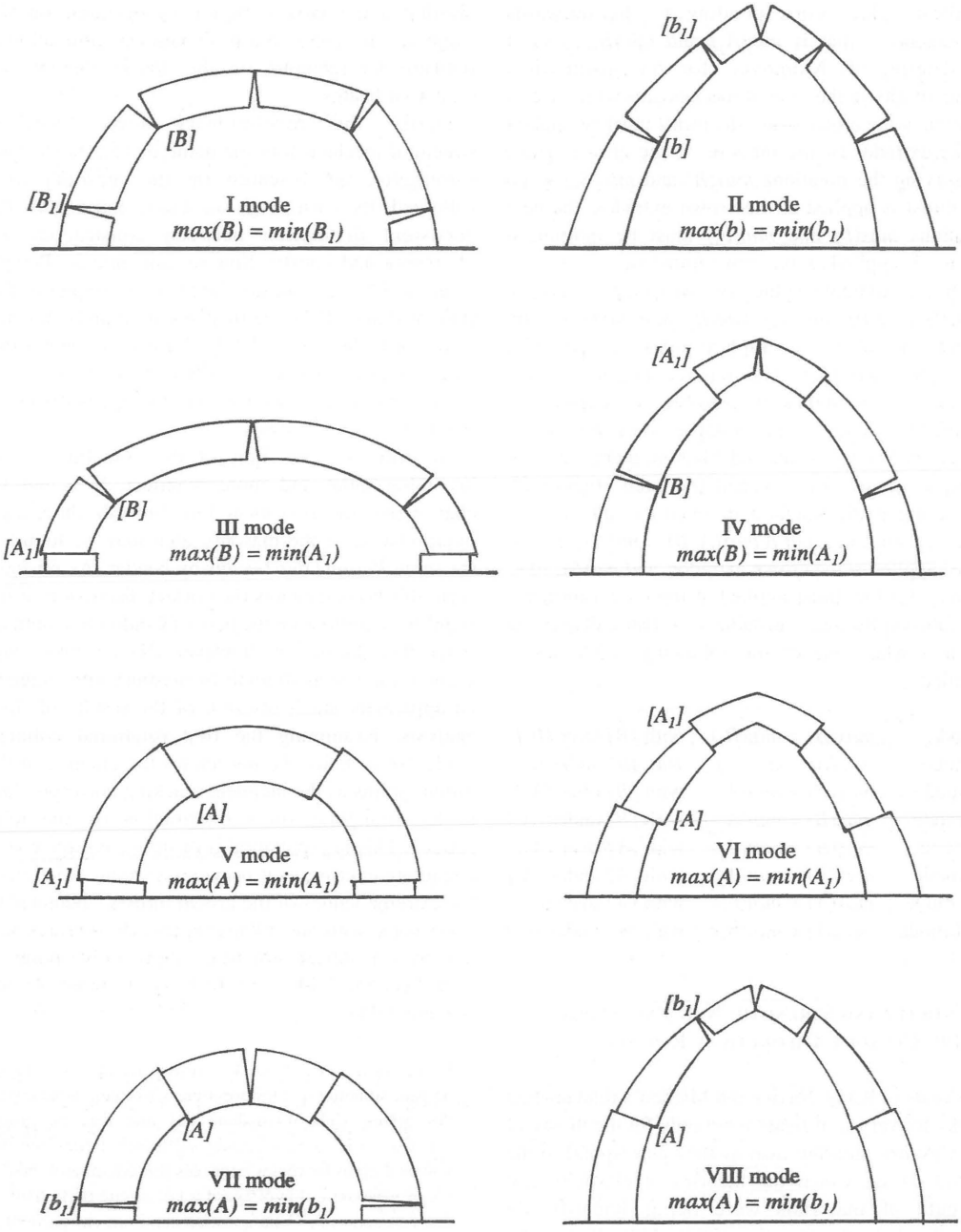


Figure 2
The eight collapse modes of a symmetric arch (redrawn from Michon 1857)

As it is easy to understand from our modern viewpoint, Navier's hint towards the elastic treatment of the masonry arch requires one to abandon the logic of the collapse approach and to set up the proper methodology for solving elastic hyperstatic systems. This methodological turn was not immediate and Navier himself did not draw all the consequencies of his idea. As a matter of fact, history shows that from Navier's hint to its conscious acceptance almost fifty years passed during which the theory of the arch tried to coinciliate the traditional approach in terms of limit analysis with the news claims in the name of strength and elasticity.

The first, and perhaps, most eloquent example of this contradictory state of things is Méry's well-known memoir of 1840. In spite of the great success of the so-called Méry's rule —the only one still quoted in to-day's textbooks— Méry's paper manifestly testifies this methodological incoherence. The first part of the memoir is an interesting discussion of the rotational collapse modes by means of the new graphic tool of the thrust line, introduced by Gerstner in 1833. In particular, Méry starts from Boistard's experimental results and Audoy's theoretical analysis in order to «translate» the limit conditions of stability in terms of thrust line. This part of the memoir is intentionally developed «dans l'hypothèse abstraite de matériaux infinitement résistants» and describe the «équilibre mathématique» corresponding to the collapse of the arch.

In the second part of the paper Méry considers the actual strength of masonry. In this case the thrust line

> ne peut donc jamais atteindre l'extrémité des voussoirs, et elle s'en éloignera d'autant plus que les matériaux seront plus mous. Par conséquent elle sera renfermée dans des limites plus resserrées que celles que nous avons considérées jusqu'à présent. (Méry 1840, 64)

These new limits are fixed by Méry on the basis of the very personal criterium for which the distance of the thrust line from the extrados and intrados «doit être assez grand pour supporter les deux tiers de la pression totale»[1] (Méry1840, 64). Méry's basic idea is summarized in the following reasonement (Figure 3):

> Nous partageons par la pensée la longuer des joints en deux parties qui doivent être soumis à des considérations tout à fait différentes; l'une [comprehending the two lateral bands DD' and dd'] dépend de la pression et de la qualité des matériaux; l'autre [the central band d'D'], dépend de la forme de la voûte. On pourra déterminer la première d'après cette condition que l'on ne doit pas attendre des matériaux un effort permanent supérieur au dixième de celui qui l'écraiserait; quant à l'intervalle [d'D'], il doit offrir à la courbe des pressions assez de latitude pour qu'elle y soit toujours renfermée. (Méry 1840, 65)

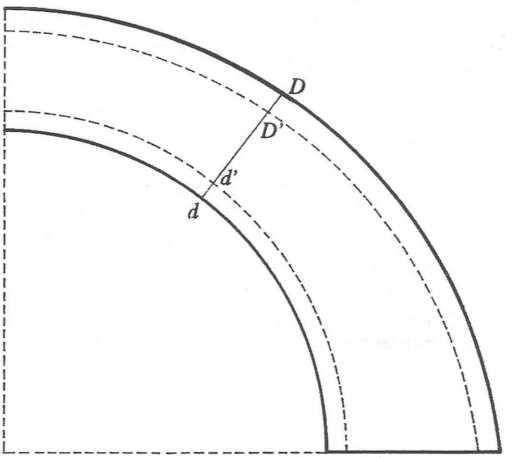


Figure 3

By this criterium,

> la question de la solidité des voûtes est ramenée à celle de leur équilibre mathématique. Ainsi, il n'y aura qu'une seule courbe des pressions possible, si l'intervalle [of the central band] est réduit au minimum nécessaire à la stabilité de la voûte; mais au contraire si, pour plus de securité, l'on rend cet intervalle un peu plus grand, il existera une infinité de positions admissibles à priori pour la courbe des pressions . . . (Méry 1840, 65).

As we can see, Méry saves the reference —also linguistic— to the logic of limit analysis and improperly takes it as the basis for analysing a stable arch with finite compressive strength. This contradictory line of reasoning is a *Leitmotiv* of 19th century literature on the arch theory. Scheffler, for instance, studies in detail the properties of the lines of maximum and minimum thrust under the assumption of infinitely resistant material. Dealing then with the «Pressbarkeit des Materials», he states that in a stable

arch the thrust line must run within a central strip whose thickness is half the arch thickness (Scheffler 1857, 69).

Another example from the American context is Woodbury's treatise. Referring to the studies on the collapse analysis by Coulomb, Audoy and Petit, Woodbury gives a correct treatment of what he calls the line of «ultimate» thrust. Coming then to consider the actual strength of masonry, he states that for a well-proportioned arch «the curve of pressure should lie entirely between two other curves which divide the joints into three equal parts» (Woodbury 1858, 329). Among the thrust lines which can be drawn within these two curves, he selects that one —called line of «actual» thrust— which passes

> through the limits already fixed; viz., at the key, 1/3 the length of the joint from the extrados, and at the reins, 1/3 of the joint from the intrados . . . We have here a perfectly distinct point of departure for a new calculation of the thrust of arches. (Woodbury 1858, 332)

For a strange way of reasoning, what should be good for the safety of the arch —that is the absence of cracking— becomes what actually occurs for the engineer's satisfaction. In spite of Woodbury's conviction of having discovered «an exact mechanical foundation for a theory of the actual thrust», we recognize here, once more, a bad compromise between different approaches.

This same compromise vitiates an anonimous *Cours de ponts* used in the sixties as textbook for the students of the École des Ponts et Chaussées at Paris. The idea that the actual thrust line must run within a central band is applied to different practical cases «d'après la nature même de la voûte». Thus, for a vault «à construire avec soin, dans des conditions ordinaires», the central band will have a thickness of 1/3 of the arch; in the case of «voûtes faites avec des mortiers médiocres ou construites dans une mauvaise saison», the central band will be 1/4 of the arch thickness; finally, «pour des voûtes executées avec perfection» the thrust will be applied to the middle point of the joints at the crown and the haunch.

Obviously, there is no reason for regarding these choises of the thrust line as the correct ones. They simply remove the statical indetermination when stable conditions of equilibrium are analysed. In other words, the central band may be useful for limiting the part of the arch ring where the thrust line should preferably lie but, as clearly remarked by Poncelet with reference to Méry's thrust line,

> cette courbe elle-même reste indéterminé, à moins de supposer fictivement la rupture de l'équilibre par rotation autour des arètes des plans de joints limités aux nouveaux intrados et extrados, ce qui réclamerait des calculs ou tâtonnements fort pénibles et peu justifiés en principe. (Poncelet 1852, 539–540)

Aims and Features of Durand-Claye's Method

The contradictory context above outlined is the background in which Durand-Claye's contribution must be placed. As we have seen, this uncertainty is fundamentally connected to the meaning of the thrust line drawn in accordance with Méry's or similar methods, based on two *a priori* assumptions for removing the statical indetermination. Some reasonable doubts arise: for instance, do those assumptions lead to a statically admissible solution in terms of strength throughout the arch ring? Do they correspond to some type of limit condition ? Where are the weak joints of the arch?

Before tackling these questions and exposing his method, Durand-Claye develops a deep discussion about the *Principe de l'emploi des courbes de pression; valeur de la méthode*. The point is the following: is the value of the results obtained by means of the thrust line comparable with that assured by the formulas of the strength of materials usually adopted for the analysis of metallic arches? To solve this point, says Durand-Claye,

> il suffit de se reporter un instant aux méthodes bien connues qui ont servi à établir les formules usitées pour les arcs métalliques: l'expérience a montré qu'en faisant agir sur les matériaux des forces déterminées et limitées, il se produisait entre ces forces et les actions moléculaires un état d'équilibre . . . Mais dans toutes ces expériences d'élasticité statique, on négligeait forcément l'étude du développement de ces forces moléculaires; on constatait un résultat. Lorsque ensuite dans les calculs d'une poutre ou d'un arc métallique, on emploie ces formules qui ne sont que l'énoncé de certaines faits . . . on vérifie seulement que le système projeté admettra les solutions d'équilibre auxquelles s'appliquent les formules; on néglige les causes mal définies qui pourront venir influer pendant la pose ou le décintrement sur le développement des forces moléculaires, comme elles ont pu intervenir

> dans la mise en expériences des tiges ou des fils qui servaient à formuler les lois de l'élasticité statique. Avec les dimensions calculées, l'équilibre sera possible, mais d'une façon mathématique on ne peut affirmer sa nécessité, puisqu'on n'est pas parti de l'état initial du système. (Durand-Claye 1867, 64)

For stone or masonry arches the formulas of the strength of materials are abandoned in favour of the graphical tool of the thrust line. Now, continues the author,

> pour que le tracé de cette courbe ait quelque valeur et soit autre chose qu'une série de constructions géométriques, il convient de définir rationellement la poussée qui lui sert d'origine. A chaque valeur prise pour la poussée, à chaque point d'application correspond une courbe de pression: on cherche si parmi ces courbes il s'en trouve *une* correspondant à une solution d'équilibre. Autrement dit, on cherche si l'ouvrage étudié avec ses charges, surcharges, profils, admet une combinaison de la poussée et des poids telle qu'en aucun point les matériaux n'atteignent la résistance limite qui leur est imposée. Ainsi recherche de *la possibilité d'une solution d'équilibre*, voilà quel est le véritable sens de la construction et des tâtonnements indiqués par M. Méry. Le résultat est le même que pour l'arc métallique: l'ouvrage admettra au moins une solution d'équilibre . . . mais nous négligeons toujours les causes accessoires qui peuvent se développer au décintrement; de la possibilité de l'équilibre, nous concluons à la stabilité. (Durand-Claye 1867, 65)

In other words, «le principe même de l'emploi des courbes de pression suivant la méthode de M. Méry, semble donc avoir une valeur comparable à celle des théories admises dans la résistance des matériaux». However,

> il n'échappe à personne que le tracé habituel de ces courbes présente une sorte de vague et d'incertitude. On n'arrive à trouver une courbe d'équilibre, que seule mérite le nom de courbe de pression, que par tâtonnements, en prenant arbitrairement deux points pour déterminer la courbe ou faisant varier la poussée en grandeur et en position, ce qui revient toujours à prendre au sentiment les deux conditions nécessaires pour définir la courbe. On n'a aucune idée du degré de stabilité de la voûte, puisqu'on s'arrête dés qu'une courbe d'équilibre est trouvée et que la voûte peut en comporter une infinité; l'influence de la résistance des matériaux n'est point suffisamment mise en évidence et les parties faibles du profil sont indiquées avec un certain vague. (Durand-Claye 1867, 65–66)

Which is, then, the right way for avoiding any arbitrarious hypothesis? Here is Durand-Claye's answer:

> Nous ne déterminerons plus, un peu au hasard, une solution quelconque d'équilibre: connaissant les profils, les charges, la résistance effective ou réduite imposée aux matériaux, nous déterminerons par des constructions géométriques *toutes les solutions d'équilibre* que peut comporter une voûte. Nous ferons ainsi une application généralisée de la méthode des courbes de pression. Cette représentation complète . . . aura sur le tracé d'une courbe unique un double avantage: 1° elle permettra de suivre tous les modes de répartition qui pourront se produire tant que la voûte sera en équilibre; elle mettra en évidence l'influence de la résistance des matériaux et montrera les points réellement faibles; 2° elle pourra de plus s'appliquer également bien à tous les exemples; elle permettra par la constance des ses procédés d'effectuer une étude réellement comparative des divers types, en tenant compte des différences de résistance et non plus seulement des épaisseurs et des profils, conditions purement géométriques. (Durand-Claye 1867, 66)

The idea is clear. Instead of searching for a single thrust line regarding it as the «actual» one, all the admissible thrust lines have to be determined. Among them also the true one will be necessarily comprised in the case of a well-designed arch. This procedure overturns the deterministic logic of Méry's or similar methods (as well as the elastic methods for hyperstatic systems). Its value resides exactly in checking the existence of admissible solutions without requiring to find the true one: as Durand-Claye writes, «de la possibilité de l'équilibre, nous concluons à la stabilité».

As it is easy to understand, we find here a particular form of what we modernly call the *safe theorem* of limit analysis. This theorem is implicit also in the stability conditions of Persy, Navier and Michon. The only difference is that now the range of admissible solutions is restricted in order to consider the actual strength of materials. In this sense Durand-Claye's method is a rational mediation between limit and elastic approach. Obviously, the ultimate condition according to Durand-Claye is not the collapse condition of limit analysis, unless one takes an infinite value of the compressive strength and neglects the tensile strength.

What we have said has been «translated» by Durand-Claye into an eloquent graphic construction based on the following steps:

Research of the admissible thrusts for the rotational and translational equilibrium of a generic voussoir

Durand-Claye considers a symmetric arch and examines the ideal voussoir between the crown joint c_0d_0 and a generic joint cd (Figure 4, left). Let's suppose that the resultant of the horizontal thrust and the weight W of the voussoir goes through the point a of cd. By varying the application point of the thrust from c_0 to d_0 maintaining fixed point a, the thrusts will then be measured by horizontal segments drawn from the crown joint c_0d_0 to the line A_0B_0; for a coinciding with c and d, the two lines $\alpha_0\beta_0$ and $\gamma_0\delta_0$ are similarly obtained, so that the area $\alpha_0\beta_0\gamma_0\delta_0$ contains the extremes of the segments measuring the admissible thrusts for the rotational equilibrium of the voussoir.

Consider now the normal component of the resultant on the joint cd. For values of the thrust corresponding to A_0 and B_0, it is measured by segments bounded by the joint cd and the points A and B, respectively; in a similar way, the pair of points α_0, β_0 and γ_0, δ_0 of the area $\alpha_0\beta_0\gamma_0\delta_0$ at the crown joint correspond to the pairs of points α, β and γ, δ of the area $\alpha\beta\gamma\delta$ at the joint cd; therefore, this area contains the extremes of the segments perpendicular to cd, which measure the normal components corresponding to the admissible thrusts for the rotational equilibrium.

To keep account of the translational equilibrium along cd, it is sufficient to draw at point a the friction cone, defined by the friction angle φ. Let's take the weight W applied at point a and consider the two horizontal thrusts which give a resultant coinciding with the boundaries of the cone. These thrusts define two vertical lines at the crown between which the extremes of the segments representing the admissible thrusts for the transational equilibrium are comprised.

To assure both the rotational and translational equilibrium at the joint cd, the admissible thrusts must be comprised within the intersection of the area $\alpha_0\beta_0\gamma_0\delta_0$ with the two vertical lines. By repeating this procedure for every joint Durand-Claye finds the area within which the extremes of the statically admissible thrusts must be included. If this area shrinks to a single point, equilibrium becomes unstable and a collapse mechanism can occur. Up to this phase, the procedure graphically translates the results already obtained in analytical terms by Persy, Navier and Michon.

Research of the admissible thrusts with respect to the strength of material at a generic joint

The innovation of Durand-Claye's method concerns the introduction of finite values of the compressive and shear strength. Let σ^* be the admissible value of

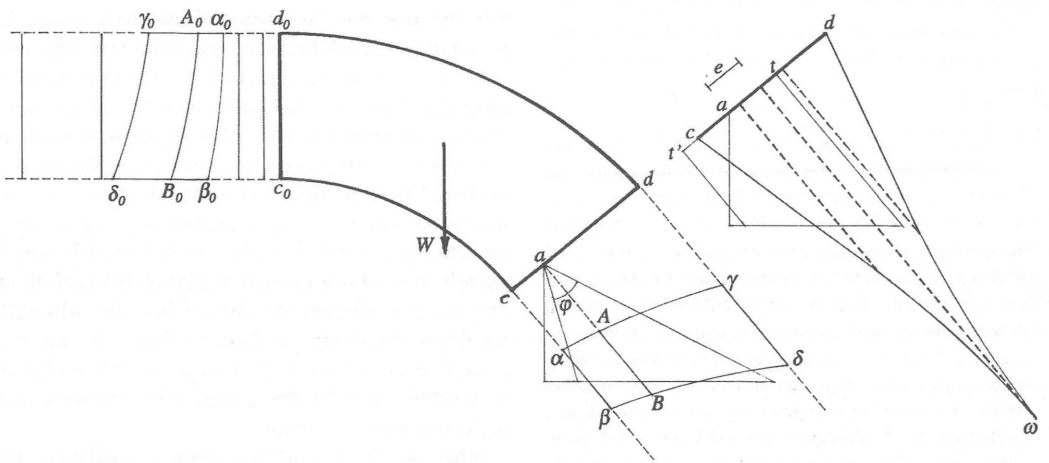


Figure 4
Durand-Claye's method (redrawn from Durand-Claye 1867)

the compressive strength, N the normal force at the joint cd and e the eccentricity of its application point. Assuming the usual linear law for the normal stress distribution, the force N for which the value σ^* is reached at the most compressed edge of a rectangular section of height h and width b is:

$$(1)\quad N = \frac{\sigma^* bh^2}{h + 6|e|} \qquad \text{for} \qquad |e| \le \frac{h}{6}$$

$$(2)\quad N = \frac{3}{2}\sigma^* b\left(\frac{h}{2} - |e|\right) \qquad \text{for} \qquad \frac{h}{6} \le |e| \le \frac{h}{2}$$

Equation (1) represents two symmetric hyperboles having as asymptotes the joint line and the straight lines $e = \pm h/6$, respectively. Equation (2) represents two straight lines with nil value for $e = \pm h/2$ and tangent to the hyperboles for $e = \pm h/6$ (Figure 4, right). Thus, the area $c\omega d$ contain the admissible normal components with respect to the compressive strength. A similar area $c_0\omega_0 d_0$ can be drawn for the admissible thrusts at the crown joint.

With regard to the shear component, Durand-Claye represents the admissible shear force S on cd by means of the segments at, at'. Applying the weight W to a and drawing the perpendiculars to cd from t and t', two segments can be obtained by intersecting these perpendiculars with the horizontal straight line from the extremity of the weight. These segments define two vertical straight lines at the crown between which the admissible thrusts with respect to the shear force on cd are contained.

Research of the admissible thrusts with respect to equilibrium and strength at a generic joint

Consider once again the joint cd and examine the intersection $\rho\sigma\varpi\chi$ of the areas $\alpha\beta\gamma\delta$ and $c\omega d$ (Figure 5). The area $\rho\sigma\varpi\chi$ has its reciprocal in the area $\rho_0\sigma_0\varpi_0\chi_0$ at the crown joint. The intersection of this latter with the area $c_0\omega_0 d_0$ provides the area $rspq$ which, in its turn, defines the reciprocal area $RSPQ$ at the joint cd. We conclude, then, that the admissible thrusts with respect to equilibrium and strength at the joint cd are represented by horizontal segments whose extremes are contained within the area $rspq$.

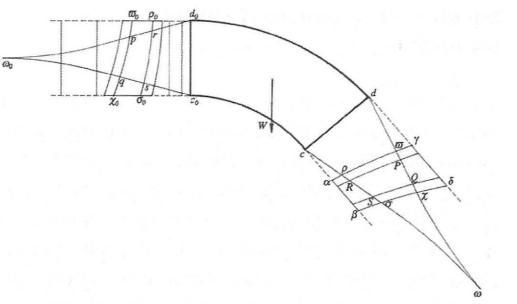


Figure 5
The «area of stability» of Durand-Claye's method (from Durand-Claye 1867)

Research of the admissible thrusts with respect to equilibrium and strength throughout the arch

Imagine now to repeat the preceding constructions for every joint. This operation defines, if it actually exists, the «area of stability» common to all the areas $rspq$. For a well-designed arch, the area of stability is a curvilinear quadrilateral of the type $r_i s_i p_j q_j$, in the sense that it corresponds to the joints $c_i d_i$ and $c_j d_j$. Its form and dimension immediately provide useful information about the safety of the arch, the position of the admissible thrust lines and the location of the most compressed joints. When the area of stability shrinks to a point, the limit condition is attained and a unique admissible thrust line exists. For example, if the area $r_i s_i p_j q_j$ is reduced to the point $r_i = p_j$, this means that the limit compression is reached at the crown extrados, at the intrados of the joint $c_i d_i$ and at the extrados of the joint $c_j d_j$.

Definition of the safety coefficient

Let $r_i s_i p_j q_j$ be the area of stability for the admissible compressive strength σ^*. By decreasing this strength, the area $r_i s_i p_j q_j$ will correspondingly decrease and shrink to a point for a certain ultimate value σ_u. The ratio σ^*/σ_u provides the safety coefficient of the real arch according to Durand-Claye's method.

Simplifications and developments of the method

The preceding construction of the area of stability has been simplified by Durand-Claye in his second memoir of 1868. This simplification is based on the fact that, by referring the line $c\omega d$ to the crown joint, two families of hyperboles —called *deformées*— can be drawn, whose intersection with the line $c_0\omega_0 d_0$ at the crown immediately gives the area of stability *rspq*. In particular, Durand-Claye applies this simplification to the case of metallic arches characterised by equal tensile and compressive strength. In this case, the admissible normal components at the generic joint *cd* are bounded by two hyperboles given by equation (1) for any value of the eccentricity. The *deformées* of these hyperboles at the crown are again two equilateral hyperboles having as asymptotes the joint line and the horizontal straight lines through the points of the middle third of the joint *cd*.

In his third paper of 1878 Durand-Claye extends the method to masonry piers and domes. In the last paper of 1880 he studies St. Peter's dome and finds that, for $\sigma^* = 10$ Kg/cm^2, an area of stability exists. This area shrinks to a point for $\sigma_u = 5$ Kg/cm^2, so that the safety coefficient for the chosen $\sigma^*$is 2.

Besides Durand-Claye's memoirs, we may quote here the contributions of Cunq (1880), who suggested a simple way for drawing the *deformées* at the crown joint, and Ceradini (1873), who extended the method to non-symmetric load condition.

«New Theory» versus «Old Methods»: what about Durand-Claye?

A glance at the historical evolution of the arch theory after Durand-Claye's contribution can help in answering this question. To this aim we take a hint from a brief report written by Jean Résal in his treatise on masonry bridges (Résal, 1887). Résal distinguishes three categories of «old methods»: 1) *Méthodes des courbes des pressions hypothétiques*, among which the names of Méry, Dupuit, Scheffler, Laterrade are quoted; 2) *Recherche du profil théorique des voûtes le plus advantageux au point de vue de la stabilité*, with contributions by Yvon Villarceau, Denfert-Rochereau and Saint-Guilhem; 3) *Méthodes des aires de stabilité*, among which Durand-Claye's work is cited. In this connection, Résal expresses a particularly eulogistic opinion:

> Remarquons que . . . son raisonnement est absolument rigoureux et s'appuie exclusivement sur les principes de la mécanique rationelle et sur la loi du trapèze, considerée comme base de la résistance des matériaux. A ce point de vue, il se sépare complètement des méthodes indiquées dans les articles précédents, méthodes dont la base fondamentale est toujours une hypothèse plus ou moins discutable. (Résal 1887, 98)

After these «old methods», Résal presents the «méthode nouvelle pour la détermination de la courbe des pressions». This «new method» is nothing but the theory of the elastic hyperstatic arch applied to masonry. The presentation of the «new method» reveals, however, some embarassment: «Nous avons réduit à deux le nombre des formules à employer pour déterminer la courbe des pressions . . . et nous avons cherché à rendre cette méthode suffisamment simple pour que son application ne parût pas notamment plus compliquée et plus laborieuse que la méthode de M. Méry, à laquelle les constructeurs sont habitués» (Résal 1887, 103).

Few years later this embarassement has totally desappeared, as Résal himself testifies in his *Cours de ponts* of 1896. By this time the elastic approach is considered as law, so that

> nous nous abstiendrons . . . d'exposer et même de signaler les autres méthodes . . . Elles ne peuvent inspirer de confiance, et comme elles exigent en général des constructions géométriques très compliquées ou des calculs laborieux, elles ne semblent pas être sorties du domaine de la théorie pour entrer dans la pratique des constructions». (Résal 1896, 190)

And what about Durand-Clay's method which had been so highly appreciated just a few years before? In the panorama outlined by Résal, it no longer has a reason to exist. Résal's words, in effect, resound the methodological position of structural engineering at the end of the 19th century. For what reason —he seems to ask— is it necessary to look for all of the admissible thrust lines when it is possible to determine the only one which actually occurs. Why renounce to the economy of thought expressed in the two compatibility equations useful for univocally determining the thrust at the crown and its point of application, when the alternative is that of resorting to exhausting graphic constructions, which leave the solution indeterminate?

A contemporary of Résal could not have opposed real objections against these questions. If the problem is that of «designing» a new masonry arch it is, in fact, reasonable to operate in order that the conditions for the applicability of the elastic analysis are likely fulfilled. Today, however, the perspective has radically overturned. The task of the structural engineer is no longer that of «designing» new masonry arches, but that of «assessing» structures which bear the signs of centuries of life. Here, then, is the question: which approach for a theory of the masonry arch?

Jacques Heyman has already provided a convincing reply, fully recuperating the structural philosophy of limit analysis since his fundamental study on the *stone skeleton* of 1966. From the modern viewpoint, the contraposition between «new theory» and «old methods» has no longer the meaning of «right» versus «wrong». As George Fillmore Swain already wrote in 1927 anticipating Heyman's position, the modern structural engineer works with the conviction that «simpler and less mathematical methods will give results quite accurate enough for practice, and perhaps as accurate as the elastic theory» (Swain 1927, 425). Among these methods there is also Durand-Claye's forgotten procedure. In effect, whenever the «deterministic» attitude of the elastic approach shows itself illusory, there is nothing but to embrace the alternative logic of limit analysis, eventually modified according to Durand-Claye.

Applications of Durand-Claye's method

The last remarks about the actuality of the methods based on the limit approach suggest a reappraisal of

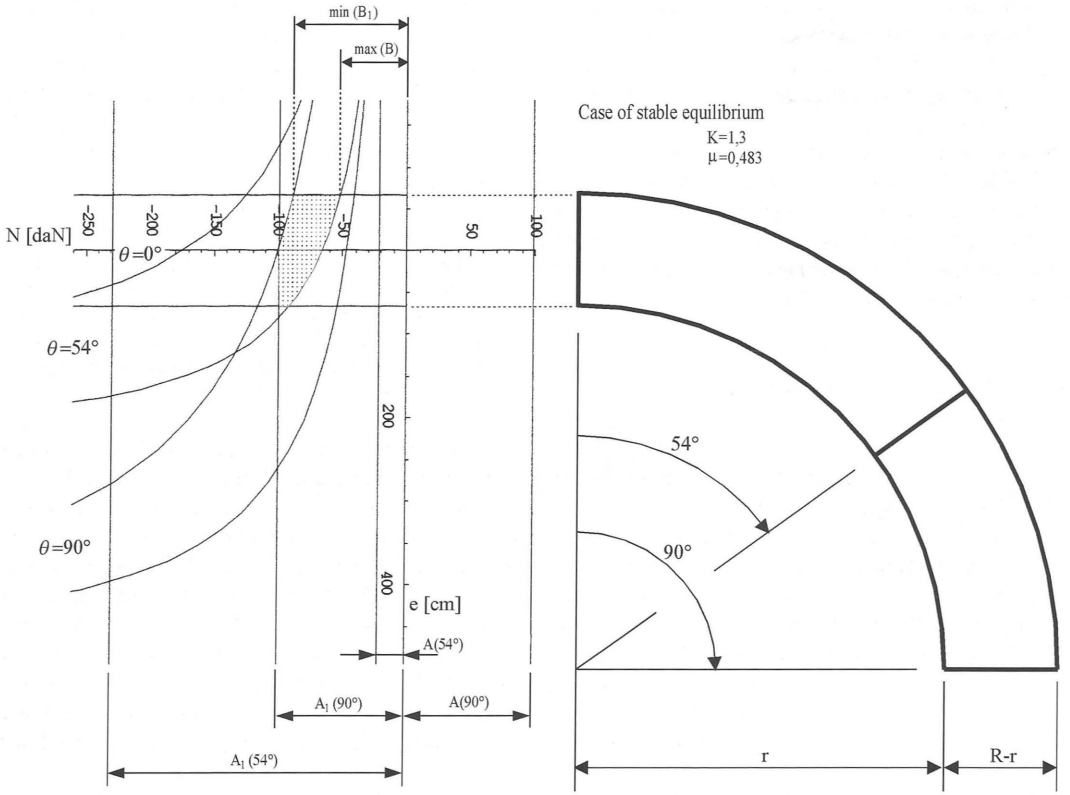


Figure 6

Durand-Claye's procedure in order to consider any tensile and compressive strength. Without presenting the mathematics of the problem, we give here some results for the simple case of a semicircular arch of constant thickness subject to its own weight (Sinopoli, Corradi and Foce 1997).

The first series of results refers to the collapse analysis under the assumptions of infinite compressive strength ($|\sigma_c| = 8$) and nil tensile strength ($\sigma_t = 0$). In this case the boundaries of the area $c_0\omega_0 d_0$ degenerates in two straight lines perpendicular to the joint $c_0 d_0$ (the same happens at each joint). Figure 6 shows the area of stability for a case of stable equilibrium corresponding to the ratio $K = 1.3$ between the extrados and intrados radius and for friction coefficient $\mu = 0.483$.

For $K = 1.1136$ the area of stability shrinks to point C (Figure 7, left) corresponding to the only admissible thrust $max(B) = min(B_1)$ and the first collapse mode can occur (Figure 7, right).

By decreasing the friction coefficient to $\mu = 0.395$ maintaining $K = 1.1136$, also the straight line corresponding to the admissible thrust for the upwards translational equilibrium on the springing joint (that is $min(A_1)$) goes through the point C (Figure 8, left) and the third collapse mode can occur (Figure 8, right).

Finally, when the range of admissible thrusts for the upwards and downwards translational equilibrium shrinks to a single value $max(A) = min(A_1)$ (Figure 9, left), the fifth collapse mode can occur for $K = 1.2205$ and $\mu = 0.309$ (Figure 9, right).

The second series of results refers to finite values of compressive and tensile strength. The ultimate compressive strength $\sigma_u(K)$ is plotted in Figure 10 as a function of K and for three values of the tensile strength, that is $\sigma_t = 0$, $\sigma_t = |\sigma_c|/10$ and $\sigma_t = |\sigma_c|$. From the curves $\sigma_u(K)$ an immediate estimation of the safety coefficient of a real semicircular arch can be deduced by forming the ratio $\sigma^*/\sigma_u(K)$.

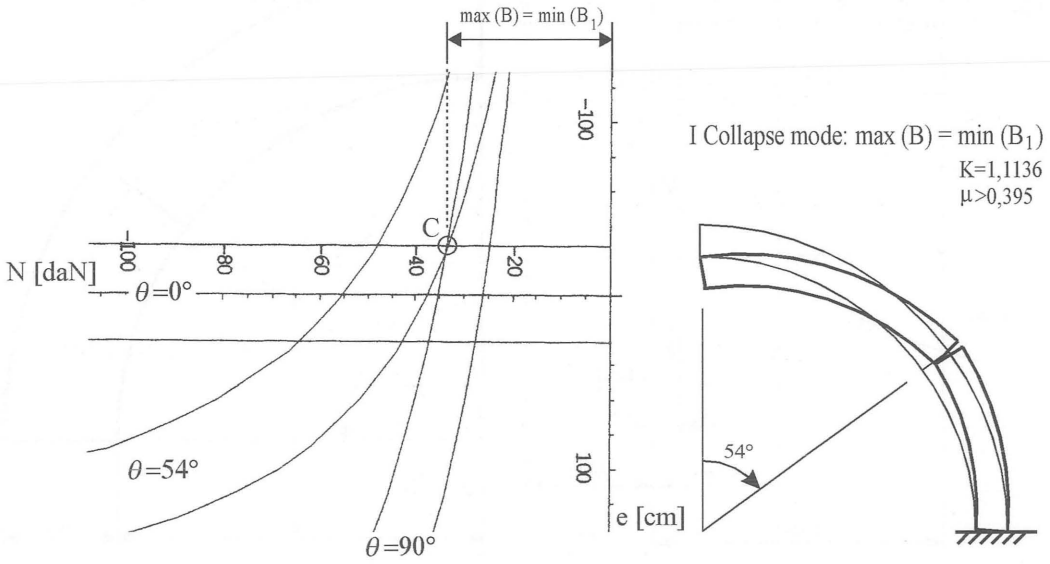


Figure 7

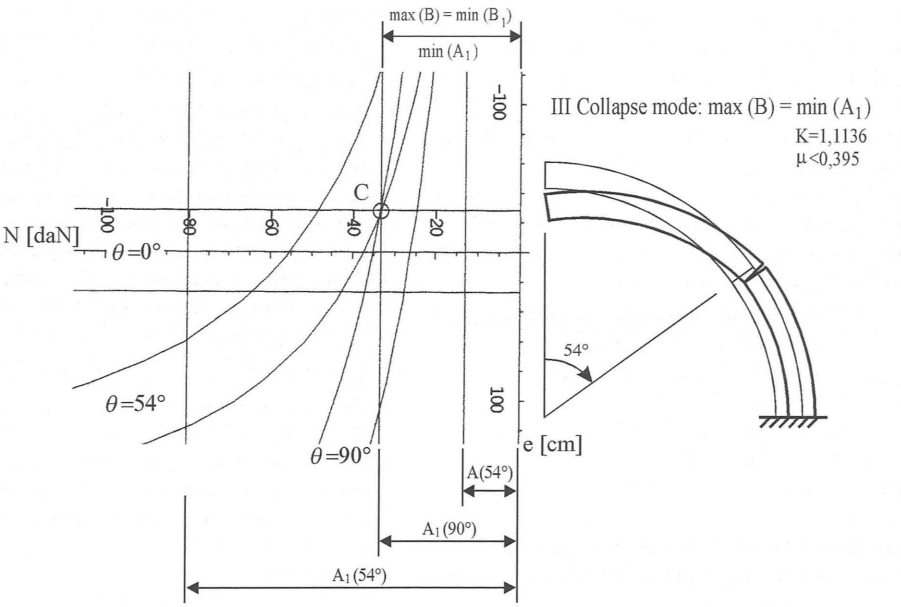


Figure 8

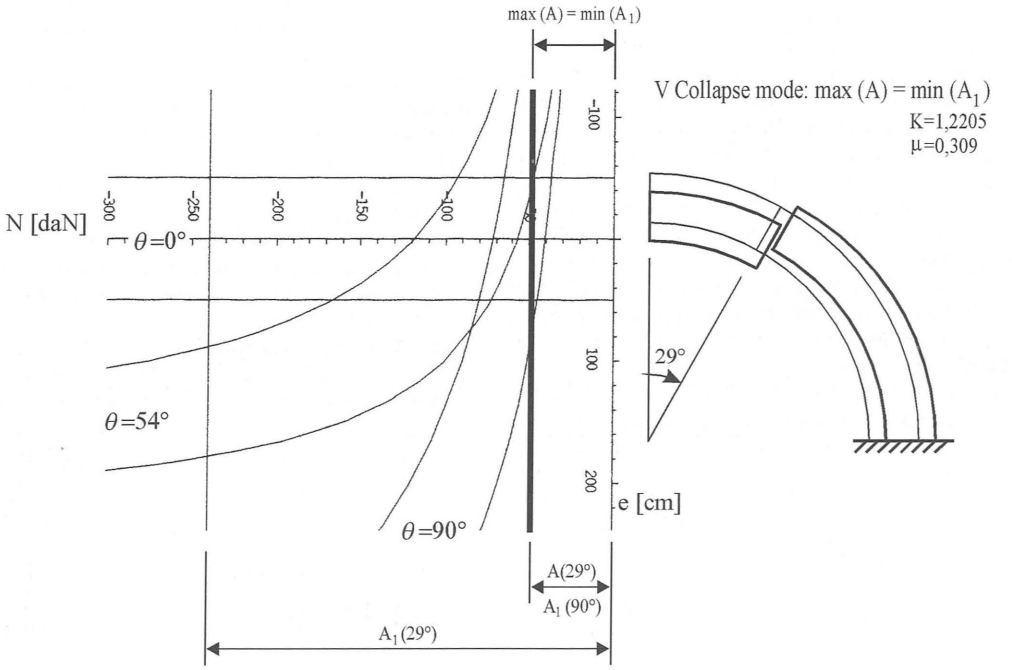


Figure 9

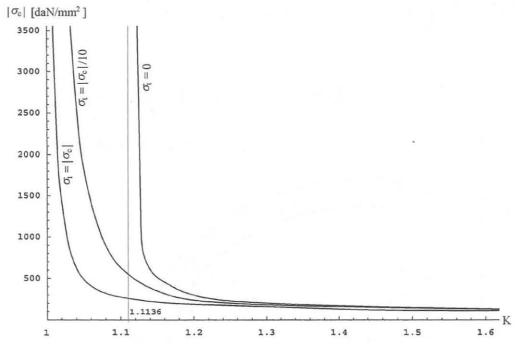


Figure 10

Notes

1. Incidentally, we observe that Méry's criterium does not correspond to the so-called middle third rule, as usually asserted in the literature.

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The timbrel vault (Extremaduran vault)

Manuel Fortea Luna
Vicente López Bernal

Extremadura is a Spanish region located at the west of the country, border with Portugal, whose administrative capital is Mérida. In its long history, we can find a dense net of multicultural relations, from oriental (Arabian, Byzantine..) up to American (discovers' birthplace as Pizarro, Hernán Cortes or Luna de Arellano..).

It's a confirmed reality that a high proportion of this region heritage has been built with vaults. Among the authors interested in the Extremaduran architecture,[1] we can often find the term «Extremaduran vaults» although without an explicit definition, everybody could understand that this term hid something more important than a mere location adjective. In the book «Brick Vaults»[2] can be found in detail the constructive process, the structural analysis an the calculus of these arris vaults. The following summary about all that is offered.

Definition

The first characteristic is its composed geometry. It is formed by the intersection of several simple figures; at the same time, each figure has a double curvature. The lack of spectacular works might justify the absence of detailled studies.Be that as it may the truth is that its geometry hasn't received a lot of atention and it has been defined as «arris vault», «lunetos» and other standardized geometric names. They can be clasified in that way, but they have a special diference, although it's very difficult to be seen, it's very important for its performance, it's to say «the double curvature». Let´s see the arris vault, the most used out of this region, it's composed by the intersection of two cylinders while the extremaduran ones is the intersection of two torus (elliptical contour) and in this way the central keystone is higher than the keystone of the lateral arches.

The second characteristic is that it is made floating in the air; it means that it is not necessary a complete mould for all the face of the vault (although sometimes it's possible to make some auxiliary arches). This aspect is wellknown by a lot of authors.

The third characteristic is the counteract, which is relied on different elements.It is known that a vault or an arch exert some lateral thrusts on their supports that must be counteracted on order to keep the balance. Usually the one in charge of this task in the vault is the support wall but when this is not enough, other resources have to be used as the «tie», the «tail», an upper overload or the buttress.

The first of these characteristics has an effect on its mechanic,on the way it works,on how the vault strengths are transmited to the wall, offering it a lot of posibilities and choosing the most convenient depending on the loads and the conditions. The strenghts coming from the own weight of the construction and from the overloads, that have to reach the floor without violence to get a permanent stability, can take several ways; what makes this vault safer and difficult to excel, unless something wrong is done.

The second is a question of economy. When an auxiliar mean as the mould is not used, the cost of the building materials and the labour force is reduced.

The third has also an economic effect. If the counteract had to be done only by the walls, they would have to be thicker; to avoid it, the counteract is divided into several elements. This obviously has a repercussion in the final result and besides interesting spacial solutions are produced.

«Retumbo» geometry

An arris vault with «retumbo» is the one whose central keystone is the higher point of itself and if we cut it in any direction will always offer a curve section, bigger at the diagonals direction and lesser at the parallel direction in the lateral walls.[3]

According to the geometry the Extremaduran vaults are all those arris vaults with «retumbo» even if they are «rosca o panderete». They are located at the Guadiana basin; towards the north up to the river Tajo, towards the south up to the Guadalquivir river, towards the east up to Castilla and towards the west up to the Alentejo Portuguese.

Construction without mould

Most of the buildings with vaults have been made with mould, this is, an auxiliar structure, generally on wood, that supports the vault or arch during the works beacause till it is not finished it can't support itself. The Romans needed a complete mould, as big as the vault was. The Gothic supposed an important advance, as the mould was reduced to the ribs. The Extremaduran vault would mean the end of that evolutionary process, in the saving of auxiliar means, getting the total elimination of the mould.

J. Albarran, army captain, reported in 1883 that the Extremaduran vault could be used as a support of another upper it with an ordinary bond.[4]

Counteract

The Extremaduran vault has several ways to produce the counteract:

1) The wall: sometimes this is not enough, taking into account the scarce thickness used in the domestic architecture.
2) The tail: uses the perpendicular walls increasing the counteract massan the weight responsible of the balance.

   Tail is called to a lengthened pendentive so that the vault arris is not born in the corner formed by the two perpendicular walls but above one of them and moved back from the other at a certain distance.
3) Other way to increase the weight in the wall is loadingin its upper part with other floor (without vault) or parapet. In this region is called parapet to a wall built along the upper front of the building that overhangs above the roof covering it and hidding the drainpipe which collects the water from the roof.

   In the buildings with vaults in the South of Extremadura, the last floor is not usually built with vault but the lower ones. The more weight the wall has on the upper part, the more resistence against the overturning. And the weight not only increases by the height of the wall but by the vertical load that receives from the roof.
4) The concealed tie: it is placed for the upper part of the vault between parallel walls.

   The tie, either in the upper part of the vault (when it's generally placed) or in the lesser one, has a work margin between null (when the wall doesn't move) and maximun which is similar to the horizontal part of the thrust. Sometimes this is a very useful resource; the Romans didn't use it, it wasn't necessary with their concrete system. The Ghotics dindn't use it either, because it spoiled their displays of willowyness and lightness.

   Our Extremaduran builders when they appeal to the tie, they do it in a concealed way, knowing that they are using a trick when no other alternative is left; but as the magician, the trick mustn't be seen by the audience. This resource is used on the front and above all on the corners. It is used a tie formed by a bar with a squared section (with the steel appearance it turned into a linkage threaded)
5) Buttress: sometimes the adjacent buildings are used and if there is anything else, a simple buttress.

The buttress although is quite common in churches . . . is scarcely used in the domestic building with vault.

Performance

As B. Bassegoda Muste said, a vault is not characterized by its shape but by its thrust. The Extremaduran arris vault due to its geometry and above all thanks to the «retumbo» can work as a rib vault or as a dome. In the first case the arris are turned into resistent ribs and the rest into supported mass. In this hypothesis the ribs transmit all the load to their respective supports, the mechanic performance would be similar to the ghotic vaults.

But it can also works like a dome since by its geometry and depending on the point and on the «retumbo», may be a «baida vault» or a piece of circular cap cut by four vertical plans.

Construction

Once the walls have been made, the following step is to fix the starting points and the point of the vault. It's called point to the diference in the height between the starting points an the lateral arches keystone. With these references you have to design four ellipses that wil be the vault sides. With the arches designed in the walls, you have to place two ropes joining the keystones from the opposite arches. The point of intersection is rised some centimetres (this's what is called retumbo). At this point a plumb is hang for the bricklayer to have a reference. The point plus the retumbo, it's to say the height between the vault starting points and the central keystone, mustn't be higher than 1'5 m, in this way the bricklayer can work easily.

Four holes have to be made at the corners where the pendentives will be. These are made with brick and mortar lime of 4 or 6 horizontal lines and the wedge forming the angle between the horizontal and the tangent to the ellipse where will be placed the first vault line.

The vault faces are built with plaster in the following way: In the ellipse designed on the wall a hole is made. Then must be done a brick arch with plaster supported on the pendentive and on the hole. Without mould and with the references of the four lateral arches and the plumb, the bricklayer will be closing the vault with consecutive lines on the four sides.

Once the vault is closed the recesses have to be filled up to the midheight with heavy stuff (stones ..). Now the vault has in its upper part a flat surface, except on the central part, where there is a spherical bulkiness. In order to get a useful surface is necessary to fill up to the central keystone; this filling must be done with light stuff not to load too much the vault.

To sum up we can say that the Extremaduran vaults are a technical constructive and structural solution, inexpensive and with a big versatility in its performance.

Experience

During the last years (with the help of trade schools) we have been trying to recover these antiques techniques that unfortunately were becoming extinct. As a result a great deal of square metres have been built with Extremaduran vaults and not only in Extremadura but even abroad.

Here you have some examples

Notes

1. De la lista de dichos autores cabe destacar las siguientes obras: Luis Feduchi, *Itinerarios de Arquitectura Popular Española;* Fernando Garcia Mercadal *La casa popular en España;* Francisco Javier Pizarro, *Arquitectura popular y urbanismo en el valle del Jerte;* Juan Carlos Rubio Masa, *Arquitectura popular extremeña.*
2. «Bóvedas de ladrillo». Manuel Fortea y Vicente Lopez Bernal. 2ª edición. Editorial de los Oficios. León 2001.
3. El «retumbo» es el nombre que le dan los albañiles a la distancia en vertical entre la clave central de la bóveda y las claves de los muros laterales. También es conocido con otros nombres, por ejemplo Alberto Gonzales Rodriguez lo denomina «resubido», y Fernando Casinello utiliza el término «arrepio». Florencio Ger y Lobez en su Manual de construcción civil editado en Badajoz en 1915, a este tipo de bóvedas las denomina «capillas empinadas o cumplidas».
4. Albarrán, José., *Bóvedas de ladrillos que se ejecutan sin cimbra*, Madrid, Imprenta del Memorial de Ingenieros, 1885., p. 13.



Figure 1
Construction practice without mould

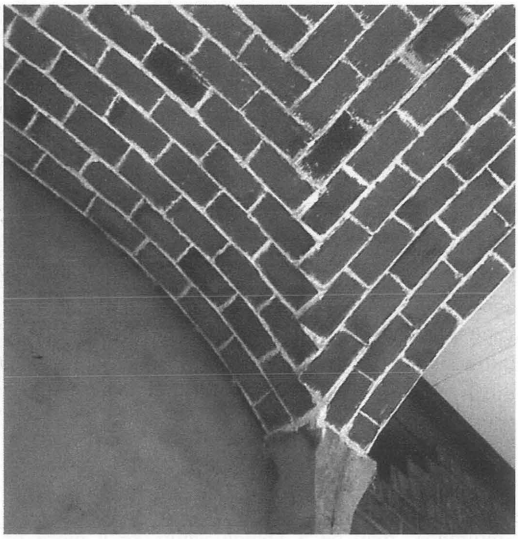


Figure 3:
A part of the bond over concrete column



Figure 2
Concrete column with overhanging for the vault support

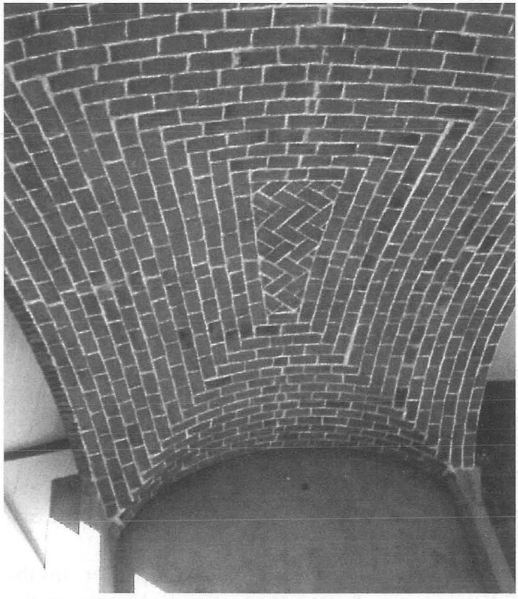


Figure 4
General view of the vault with 4 supporting points

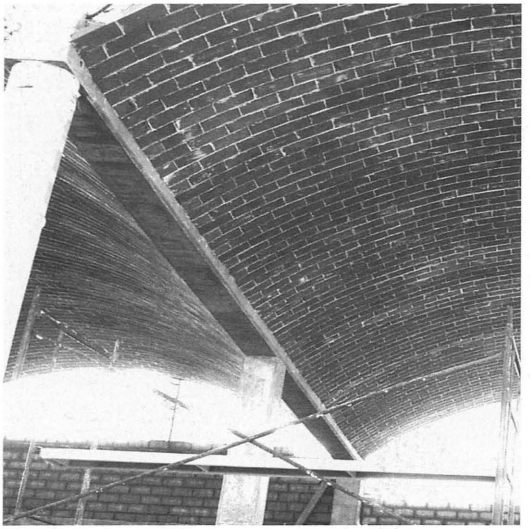


Figure 5
Vault with lineal support over reinforced concrete beam



Figure 6
Vaults with different bonds over beams in double projection

Teaching Construction History

Giovanna Franco

Questions about education and training

The school of Architecture of the University of Genoa is characterised, at least since the last ten years, by a huge number of teaching courses devoted to historical building technology (in the degree course, in the School of Specialisation in Building Restoration, within the PhD course in «Building and Environmental Recovery»). This probably depends, among the others, on the fact that Genoa has one of the biggest European historical centres, that has been developed, since the Roman period till XIX century, with continuous stratifications. The knowledge of ancient building techniques becomes therefore a crucial issue, especially to preserve the historical heritage from wrong interventions, that could damage materials, load bearing structures and the image of the historical city.

Among the different disciplines that study the ancient construction, the paper deals with one specific discipline, the «technology of the construction», which main goal is to analyse the building in its physical consistency (materials, elements, structural behaviour and state of conservation and/or decay). Of course this discipline could not be seen as autonomous but should be integrated with other analytical tools and methods, sometimes more scientific and less «qualitative», like chemical and geological analysis on materials, archaeological introspections, archivist analysis.

A «technological» analysis of the historical building, in fact, looks at the object as a product of a building civilisation and aims to interpret the relations between materials, working tools and methods, building construction practises, shapes and spaces configuration, building settlements rules and models and building yard's organisation (Blachère 1966; Dupire 1981).

Anyway, the significance of building constructive analyses exceeds the pure historical «curiosity». The focus point is the objective of this kind of studies that seems like a journey through a centuries-old heritage of human skills that keeps the cultural values of a city or a landscape and, at the same time, it is continuously under modification (Cacciari 1993; Gregotti 1984; Pedretti 1997).

The paper is focused on the role that this kind of teaching could joke inside the university and professional education and deals, therefore, with the following relevant nodes, not only focused on the knowledge of building construction progress but, moreover, on the influence that the construction technology had in the past, and still have, on our contemporary culture:

- the purposes of the construction history studies,
- their validity inside historical disciplines,
- their role in relation to general questions regarding the future of our tradition and the way to innovate it.

The role of the knowledge of ancient building for their preservation

Ancient builders in Genoa and inside the Ligurian region were able to develop a complex construction tradition using simple and poor materials (stone, wood, slate) and facing an hostile landscape. Nevertheless, they created a variety of technical solutions that are nowadays difficult to be understood, especially using the contemporary calculation methods. The first correct approach, facing an old building, is to look at it trying to understand the nature of materials, the way to work and to put materials together in order to create elements, and the structural conception of the whole building This kind of investigation fits together with other historical studies, from which is different, but at the same time complementary, because it is based on a synthetic, qualitative and sometime intuitive view. Few examples could better explain this crucial issue.

Pitched roofing structures in Genoa from XVI to XIX century

In the historical buildings of Genoa and Ligurian region it is possible to discover a strong relationship between the load bearing masonry structure and the roofing system. While the vertical load bearing structure was heavy and massive, made by incoherent stone and brick masonry using as less as possible mortar between joints, the roofing structure was more light and elastic, to avoid any structural failure, especially in the angles.

Since the Renaissance and till XIX century, in fact, ancient builders used a unique and fine technology to cover residential buildings (the «palazzo» and the «villa»), different from all the other Italian countries. This particular technology allowed to realise a closed system, with diagonal beams supported by another structure and, consequently, the angle of the building was not interested from any thrust. The kind of roof that derives is solid, but at the same time a light and elastic structure, similar to the ship shell. Like the shipping technology, in fact, the roofing shell is supported by a primary structure like the wooden ribs, reinforced by other supports (Galliani 1984; Galliani and Franco 2001).

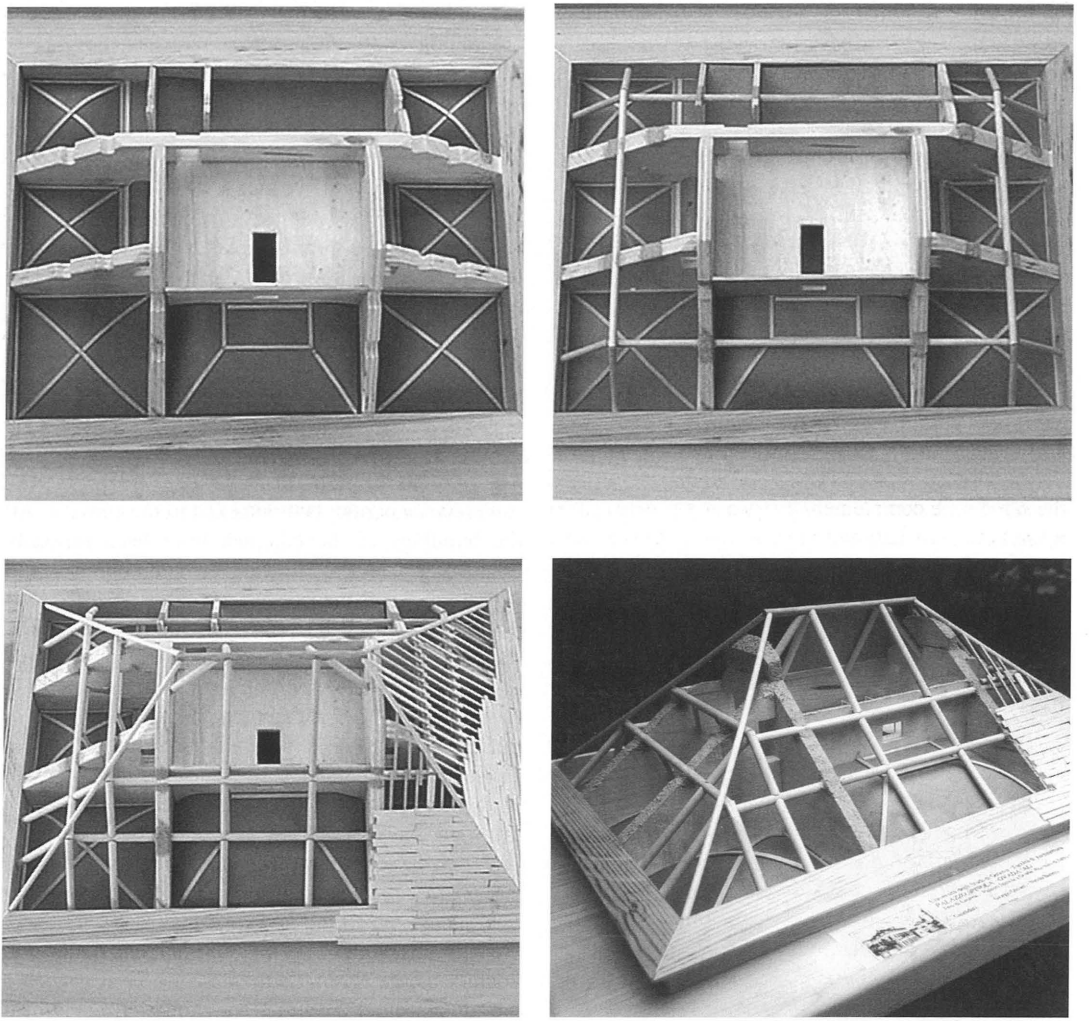
This particular system is characterized by a structural behaviour that is completely different from the other traditional wooden roofs: the principal beams are located on a massive part of the external wall, close to, but not over, the angle, that is a weak point of the incoherent masonry vertical structure, Figures 1,2,3,4. The braces are supported by other beams so that, in spite of their length, they are thin and light. All the structure is then stiffened by a wooden planking, that contributes to the whole resistance of the roof. Each element is not separate from the others, like in the contemporary building, but is part of an integrated system, like an «organism», where each part has a specific role and determine, but at the same time depends on, the whole.

This very particular technology lasts from the Renaissance to the industrial revolution, when the use new materials, especially iron and cast iron beams, starts to modify structural conceptions.

Flat roofing structures in Genoa from XVI to XVIII century

There could be found lot of examples of particular techniques in the traditional building yard. Another example, that is just a pretext to develop more general problems, is the way to solve, in the past, another huge problem: the flat roof, used as a terrace.

As we know, the flat roof is one of the major issue of the Modern Movement, but at the same time is one of the main technical problem, because of water infiltration. Ancient builders did not have at their disposal steel or reinforced concrete beams to cover huge lengths in terraces, neither waterproof membranes to protect inner spaces from rainwater. Nevertheless, they developed a brilliant solution to solve both the problems: the way to cover enormous length (also 10 meters) and the waterproofing. They invented a double roofing system: first they were used to build a pitched roof, made by wood structure and covered with a slate mantle, to guarantee protection from rainwater. Over this structure they built a flat terrace, supported by parallel brick walls, as lighter as possible. This goal was reached through a very light, but at the same time resistant, load bearing structure, made by thin bricks arranged like a «castle» made by play cards, Figures 5, 6. In case of infiltration of rainwater from the terrace, the pitched roof did not allow its penetration inside the building and the inner spaces. The technical innovation, in this case, is not in



Figures 1, 2, 3, 4
Constructive phases of the roofing system in the Palazzo Spinola in Ovada, Italy (XVII century)

the material but in the way to dispose it and the resistance of the structure is guarantee by its shape.

The knowledge of ancient technology is therefore and first of all necessary for any operation on the historical heritage, both for its conservation and for its modification. The courses organized in the School of Architecture intend to prepare the students to face practical problems using a logical approach for the investigation and the understanding of general behaviour of ancient buildings, apart from the specific cases.

Unfortunately even nowadays it is possible to assist to many invasive and incoherent interventions that transform, where not demolish, ancient structures, just because technicians are not able to understand their behaviour and to trust their performances anymore.



Figure 5
Example of the system to support a flat roof, used ad a terrace, in a palace from XIX century in Genova, Italy

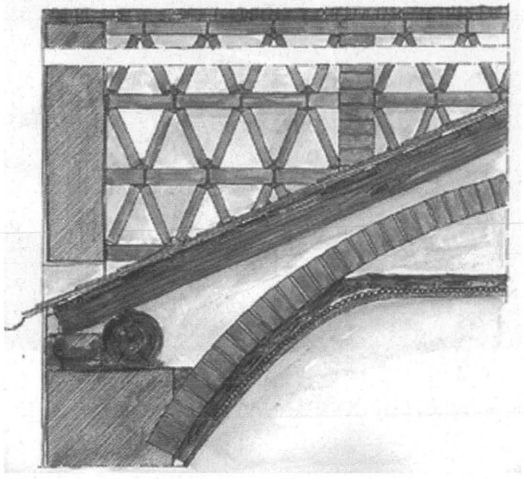


Figure 6
Section of the double roofing system in a Villa built in the XVII century, Genova, Italy.

Tradition towards innovation

The knowledge of ancient construction technology is not only important for the conservation and restoration of the built heritage: it is the key for the innovation, that is the real essence of any project and design process. Any innovation in fact, even if it aims to break a tradition, comes up from a deep reflection on the tradition itself. This is a general sentence that is valid for materials, elements, structures, for the whole building. Any contemporary architecture, if it is a good architecture, even if it wants to fight against the past, has its basis on that (Colquhoun 1989).

Following this principle, it is possible to find different examples of new design that solve the conflict between tradition and innovation.

The following example comes again from the genoese tradition. The object of the project was the restoration and structural rehabilitation of an old convent of S. Ignazio (dating from the XVII century) for the new Historical Archive of the Columbus fund. The complex contained a pre-existing villa, from the Renaissance period, later annexed to the convent. All the buildings of the complex have been seriously bombed during the World War II, and no one of them was anymore covered.

The main problem to solve, among the others, was the construction of a new roof to cover and protect the inner spaces of the villa, which stuccos and frescos, in fact, were damaged by rainwater.

The first question raised by the experts involved in the project (A. Buti, G.V. Galliani, A. Sibilla, 1990) was about the way to built again the roof structure for the villa. Was it possible to build a new roof similar to the original? And how was the original? No historical documents were found neither any original trace was available. Nevertheless, the knowledge of other examples, as above explained, allowed the experts to advance some proposals. The idea to build again a wood structure like the traditional systems was discarded, at least for two reasons: the impossibility to find long beams as good as the original ones and the lack of ability of contemporary carpenters and builders.

Anyway, the knowledge of ancient structures helped the experts to design a new roof, which structural behaviour is similar to the original one. The main façade of the villa is in fact composed with a wide opening, creating a loggia, in the upper part under the roof, and this opening should not be pressed by any force deriving from a new covering, Figure 7.

The adopted solution consists in a new structure, made by laminated wood, that is supported by the same parts of the load bearing masonry that probably supported, in the past, the original roof, Figure 8.



Figure 7
The main façade of the Renaissance villa inside the Convent of S. Ignazio in Genova, Italy (XVII century), before restoration and roof reconstruction.

The path traced by ancient builders guided the contemporary technicians, that expressed their innovation both in the choice of material and in the structural conception.

The examples that have been considered in the paper, limited to a very specific and restricted context, could easily be extended to a larger field. Every new architecture, if it is really good, is based on the knowledge of the past, not only from a formal point of view, but also from the constructive and structural point of view. This is true especially looking at famous masterpieces, that contribute to define new scenarios in the history of architecture and building construction, Figures 9, 10, 11, 12, 13, 14.

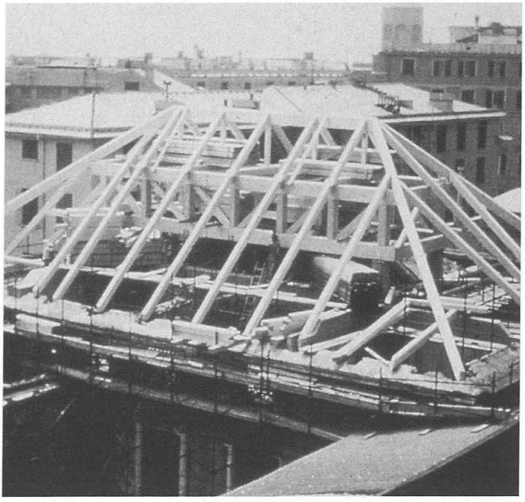


Figure 8
Reconstruction of the roof of the old villa, with laminated wood elements and a new structural conception, with the same structural behaviour of the original.

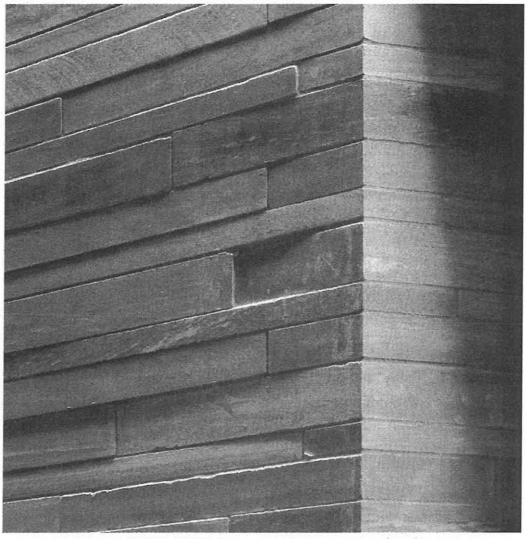
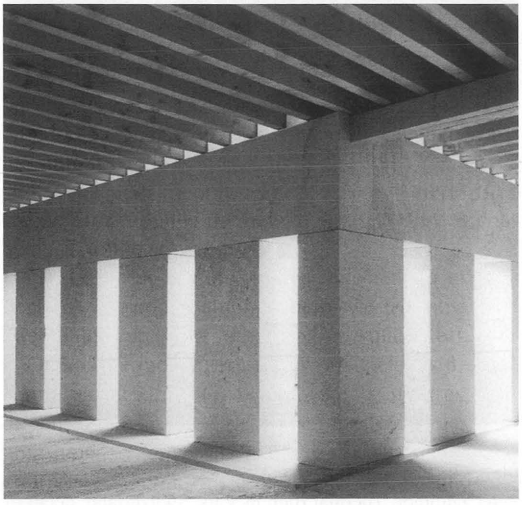


Figure 9
Peter Zumthor, Thermal Bath in Vals, Switzerland, detail of the wall (1990–1996). The building is a contemporary interpretation of ancient roman bath and, at the same time, of the traditional alpine buildings in the surroundings. The constructive technology re-interpret the massive stone masonry, characterized by the stratification of horizontal layers, using local gneiss stone, disposed in layers, as a formwork for the reinforced concrete casting.





Figures 10, 11
A confrontation between La Saline Royale d'Arc et Senans, France, by Ledoux, and a private villa on the Lake of Garda, Italy, designed by Carlo Scarpa. The column, as a classical element, is not only used, by Scarpa, to recall the pure shape, but again is a massive structural element, made by stone or concrete disks overlapped.





Figures 12, 13
Gilles Perraudin, vinery in Chemin des Salines, Vauvert, France (1996–1999) and the Pont du Gard. The architect choose a place nearby the famous roman bridge. Instead of using a contemporary high tech language, like he is used to do, the architect has been influenced by the presence of the great roman infrastructure. He decided to use the same stone, extracted in the surroundings, coming back to the oldest way to put one piece on the other, without using mortar. The innovation is just limited to the organization of the building yard, where new technology allow to rise the building just in few months, in spite of the weight of the stone blocks.

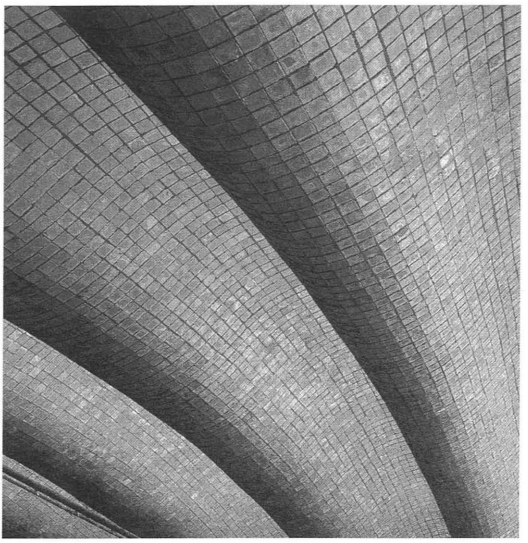


Figure 14
Eladio Dieste, storehouse in Montevideo, Uruguay (1979), double curved vaults. The engineer invented and created new structural typologies, like the reinforced brick vaults, using a traditional and poor material, thin bricks, to define complex and double curved vaults, which shape contribute to the structural resistance. His work could be seen also as a development of the catalan «boveda tabicada».

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Typological study of the late medieval galician towers: Application to the restoration of the tower «Torre de Vilanova dos Infantes»

Manuel Freire Tellado

The intervention in values of cultural interest is a very delicate matter due to several reasons, as the following ones:

— they are elements of great value of reference for the community where any action awakes an extraordinary social sensitivity;
— the superposition of multiple actions realized on them throughout the history-actions that have completely ignored the values of the original construction distorting or, at least, changing them significantly, thus making the comprehension of the object inmensely difficult;
— the time distance and the methods that served to erect them, a distance that has not only affected the constructive techniques but also the way of thinking: at present the actions are based upon a conception which is derived from the scientific method and the analysis of the problem by parts, whereas the historic buildings have been constructed within an integral mentality and not precisely a scientific one.

At present the intervention is conceived with the following criteria: differentiation —clear differentiation of the limits between the intervention and the original building should be made; reversibility of the action— its possible elimination at any moment. The authors not only want to maintain the patrimony but also to contribute to new pieces for the creation of new cultural heritage.

It seems logical that the project maker should look for all possible support to eliminate the major number of uncertainties in his intervention, beyond the mere fulfillment of legal requirements. Within this philosophy the support of the historical analysis is as much a legal necessity as it is an instrument that will achieve great value.

Unfortunately the historical-artistic memories compelled by the standard are usually reduced, probably besause of the lack of understanding between the historian and the architect, to an endless list of dates of outstanding local historic events having some kind of connection with the building but without any relevant information about the structure itself. The importance of chronological information and historical evolution is not denied yet the necessity of completing this information by a different one is emphasized: it means that the information to be obtained should have both vertical sense, i.e. time evolution, and horizontal sense, i.e. the events that take place in a coetaneous form, and above all dealing not so much with the happenings as with the building itself. So the information which is proposed as a relevant one is surely the historical and chronological updating, treating equally (or more) the history of building masonries, the events that have taken place and also the historic-typological study which means how the edification type of the building is resolved in the time zone and geographical proximity.

In short, a double line of investigation of the history of the construction is realized: first as a building and second as a complex of edifications with their typology. The first enables to comprehend the building, the second points out its peculiarities and gives guides for the proposed interventions.

The previous reflections came up during the development of Centro Comarcal de Celanova project as a consequence of the first prize obtained at the competition which had been summoned for that purpose. The above mentioned construction had to be established as an ensemble of the tower and the two houses near the medieval tower of Vilanova.

The difficulty of the process is manifested by the fact that in Galicia, which is considered to be a land of castles (more than 800 of them are classified), there isn't any typological study on the castles referring to the mentioned time. That is why a minimum classification is made.

The environment of the study is restricted to those defensive buildings among which one tower —Torre del Homenaje, is the main motive of the edification. It is not a matter of great castles but a single tower isolated or defended by walls always being within the criterion of fortification where the concept of defensive levels is clearly defined, among which the tower (la Torre) is the last refuge. Towers that are independent or pseudoindependent elements, perfectly recognizable as objects in the edifications whose mission is no longer to defend a town but a personage who shelters in the Tower.

These defensive concepts can not isolate the appearance of arquebuses and the first fire arms, the fast development of which will during a century provoke the radical transformation of the defensive systems and the dissappearance of the type under study.

The relative homogeneity that is perceived in the solutions of that time is linked with both the quality of the type and the fact that those buildings frequently changed within the complex world of Reconquest, succeeding fights, dislikes and confrontations between the noblemen and the church of the early medieval Spain.

The History of Vilanova and its Tower

Vilanova is a little town of medieval layout situated very near to the little town of Celanova, Ourense, Spain. The tower of Vilanova dos Infantes is a medieval tower that formed a part of second line of fortifications of ancient frontiers with Portugal, named «raia-seca». At present it is classified as heritage of cultural interest (BIC —Bien de Interes Cultural).

The surroundings of Vilanova show traces of preroman human occupation since the time of celtic (castreña) culture: Castromao, 2 km. from Vilanova, was a «castro» of Coelerinos occupied since cc. YI-V B.C. until c. II A.D. Some authors emphasize the influence of this epoch and even speak about the «castreño» arrangement of the present hamlet in Vilanova.

The roman influence is manifested in an ancient roman roadway that reaches the town from the east. In the town itself an ashlar stone of a house of Plaza Mayor is conserved —roman Ara Votiva dedicated to the gods Lares Gumelaecos. Its probable origin in the zone confirms a profound romanization of the place.

There is no information about the place from the late roman time until the time of repopulation (La Repoblación) after the expulsion of the muslims.

The X century is the most important historical period marked by the appearance of D. Gutier Menéndez, the father of S. Rosendo, who in 936 establishes the benedictine monastery of S. Rosendo of Celanova in whose masonry the dictates of the regulation of the religious order «Ora et labora» are noticed. In this monastery in 944 S. Rosendo will retire for a period of time for a temporary rest from his hard work.

Vilanova dos Infantes used to be a reliable residence for S. Rosendo's mother and sister —Dª Ilduara and Dª Adosinda respectively; and also for other women of the royal family who belonged to its twin Santa Maria de Villar monastery founded in Vilanova by the year 940 by Dª Ilduara and later annexed by Celanova monastery.

The transcendence of this zone in the Middle Ages leads to the idea that Alfonso X el Sabio was educated in the nearby castle of Maceda afterwards establishing his court in Allariz at about 10 km. from Vilanova.

Despite the closeness of Celanova monastery, Vilanova was independent of the ecclesiastic nobility and belonged to various lords who were ruling in the name of the king. The count D Gutier Menéndez and DªIlduara ordered to build the Vilanova castle

(Silveiro Cañada ed. 1974, vol 30, voz Vilanova das Infantas). In 1369 Enrique II El Bastardo captures the castle of Vilanova from Fernando de Castro, the count of Trastámara Lemos and Sarria and who was made count by the king Pedro I de Castilla (Vazquez [1972] 1990), to give it D. Juan Rodriguez de Biedma as a reward for his services in the struggle for the throne of Castilla against Pedro I, among the so called Mercedes Enriqueñas (Eguileta, 1994, 514).

The Monterrei family inherits the fortification from the Biedma family. The Castro family —the counts of Lemos, dissatisfied with this transfer conducted a lawsuit against the Monterrei family, but the sentence turned out advantageous for the latter.

The tower was destroyed in 1467 when it belonged to the count Monterrei (Castillo, 1972, word «Villanueva de los Infantes»), as a consequence of the Irmandiños rebellion against the galician nobility. The destruction was complete according to the obtained reference. It was reconstructed between 1481 and the middle of XYII century as there is evidence that the tower was again used by the year 1645 during the war between Spain and Portugal which led to the second and final independence of Portugal. De Prado (1986) points out that the tower was reformed in the XYII century by new defensive concessions which degraded when the tower was abandoned.

Fariña Busto (Silveiro Cañada ed. 1974, vol. XVIII, voz Fortalezas) classifies it in the gothic phase; while Basilio Cegarra (Begarra, 1995) places it between the cc. XY-XYI. In our opinion the tower belongs to the late medieval typology. We have taken into consideration the similarities with the fortifications of the epoch, which are obtained from the corresponding typological analysis: constructive features —stonecutter's marks, pointed arches in voids with big voussoirs— the principal balcony. Typologically they differ from the fortifications of the previous epochs in the predominance of the tower, and which could perhaps be linked with the new necessities and techniques that brought about the first fire arms. The arquebus appears somewhere between cc. XIY-XV, but when these have not yet provoked the revolution of the fortifications that would originate later.

Moreover, already in the penultimate decade of the XVI century in Spain appear theoretical proposals of fortifications with bastions that even before the end of the century are planned for concrete points, for example the port defense of A Coruña (4). It doesn't seem logical that already having systems of major defensive efficiency a reconstruction of the old use would be put up, taking into account the fact that it is a boardering and conflictive zone and that the north of Portugal is strengthened by constructions of a new stamp. As a constructive period appears in Celanova around 1550, i.e. the construction of Claustro de las Processiones, that shows the economical power of the time, the reconstruction in our opinion takes place between 1481 and 1550.

Subsequently, since the Desamortización de Mendizábal, the tower has been used as Town Hall (Casa Consistorial), which is proved by the date 1825 which is engraved on the entrance doorhead. This usage will remain until january 1927 when the town hall of Vilanova is taken over by the town hall of Celanova. And after its abandonement it is used as Court (Juzgado) until 1992–1993 when it is restored to be used by Municipal Music Band.

As for the hamlet of the town of Vilanova, it follows the barbican line. There are two main types of houses. The first, of better design an concerted rubblework, corresponds to the old heraldry houses: the arms of Limias, Cambas, Feixoós, Enríquez . . . are among there stones. The second type is used for the construction of more popular houses. They consist of two floors with the second one sometimes overhanging, surrounded by wooden balconies of precise design and generally with a direct access from the street by the exterior big flagstone stairs, while the ground floor is or has been used as a stable.

The History of The Tower Building

By now the existing ensemble has been formed by two towers, one inside the other. The interior structure parallel to the walls of the visible tower is by origin prior to the «irmandiña» destruction (Eguileta, 1994, 521). It extends up to a level which is inferior to the present level of access. It forms a part of the primitive tower destroyed by the mentioned rebellion, linked without any doubt with the walls of the ancient castle of Vilanova, which had to be an exterior tower bastion, as it is demonstrated by alignment of its walls with the rests of the rampart lines as well as the greater thickness of one of its four walls, the

alignment with the ramparts, and the visible exterior traces of the joint of the tower masonry with some transversal element.

The tower which is visible nowdays is of a later period, as it is shown by the independence of the exterior walls from the walls of the interior structure mentioned before. The lack of a bond between the present tower walls and the rests of the transversal walls as well as the difference of the composition of their masonries, i.e. concerted rubblework contrary to the exterior squared ashlar masonry, and also concrete constructive questions, i.e. the stonecutter's marks and pointed arches in voids with big voussoirs similar to that of the principal balcony, supposes its realization in the late medieval time, probably between 1481 and 1550.

The tower undergoes a great transformation in the first quarter of the XIX century to adapt it to its new use as Town Hall. Among the realized modifications (Eguileta, 1994, 529) are: the addition of the staircase which at present serves as an entrance; the substitution of the loopholes by large rectangular windows; and the entrance door aperture at the north eastern side (the year 1825 is engraved on the doorhead). The addition of the staircase would conceal the traces of the junction of the rampart from this side, as it is precisely of the height where the staircase reaches its maximum elevation at which the linkage should be realized. These transformations have irreversibly changed the image of the tower.

Finally, in the period of 1992–1993 the tower was conditioned for its use by the Municipal Music Band eliminating the hip roof crowning it, by fixing a number of horizontal levels, placing a staircase and an empty vertical space that crosses all the floors of the tower.

The preceding lines are the result of the support of the historical investigation of building comprehensiveness but it turns out to be too little for the desired purposes. To accomplish it and to understand the constructive and design peculiarities of the tower of Vilanova, the study of different examples of the surrounding medieval towers is brought up.

Initially the study was centred on those examples that resulted to be closer to the author who systematized them in a second phase. Thus, at first, the towers of Monforte de Lemos and Castroverde, both being the possessions of the Castro family —the counts of Lemos, were visited and analyzed being the second ones in likeness with that of Vilanova. The reconstruction period of the Vilalba tower, about 1480, and its connection with the Castro family (it belonged to D. Fernando Ruiz de Castro) resulted in its inclusion among the studied ones.

Later the investigation was systematized, covering the principal medieval fortifications of Galicia, putting an emphasis on those which are in the interior part of Galicia, linked with the four powerful families: Biedma, Monterrei, Lemos and Andrade. A specially detailed study was done on the fortifications corresponding to the terrestrial frontier with Portugal and belonging to the province of Ourense: the «raia-seca», i.e. fortifications of Sande, Vilanova, Milmanda, A Porqueira, Monerrei, and on the second line —Sandiás, Celme and Pena. The election of the mentioned families is justified knowing that the first three ones had for a definite period of time the possession of the fortifications we are dealing with, while the family of Andrade is responsible for a significant number of defensive buildings in the north of the community, and the possession of many of them passed from the family of Andrade to the family of Lemos in such a way that an interaction among the solutions referring to the fortifications is quite probable between the two families.

The study was centred on the models of single towers. Meanwhile other important galician fortifications as the Castillos de Pambre y Sobroso deserved a more superficial attention centred on: the finial systems, i.e. coblestone (continuous peen) over brackets (stone corbels); the reinforcements on the basis of fortification turrets in Sobroso and embattled finials over the corbels in Pambre.

The analysis of the Monforte de Lemos tower, lightly restored in 1975, permitted to analyze the system of embattled finial at the overhang over the stone corbels, to understand the constructive meaning of the continuous stone corbels of the last floor prepared to receive a wooden dormant that supported the wooden horizontal plane (forjado), and also to understand the unitary purpose of the space of each floor for common use. So it can be seen how the changed disposition of horizontal plane (forjado) direction makes the stairs modify their position on the different floors. In this tower the entrance is of middle height but an incorrect decision of attaching a stone staircase to it eliminates any perception of it as an entrance.

However the dimensions of the tower of Lemos give it such a splendour that the Vilanova tower

doesn't have and also a number of constructive features that differ them as for instance the presence of a flat arch as a roof support or the configuration of a three dimensional battlement perhaps connected with the appearance of the arquebus.

Therefore the study interest was focused on the tower of Castroverde which by now has not yet been an object of restoration. It rises solely in the centre of a small defensive perimeter, undoubtedly of the previous epoch, as it has certain formal likeness with the solutions of the Castle of Castro Caldelas (also of Lemos family) as well as with the reinforcement system with fortification turrets. The tower is very similar to that of Vilanova both in form and dimensions. The entrance is realized by means of an opening of middle height configured by a doorhead that lies on overhanging corbels over the bay. Fortunately the absence of restoration permitted to appreciate the interior empty space of the tower after climbing about 3,5 m which, as a solution of purely defensive character, now separetes the access from the ground level. In this case the corbels for supporting the dormants which would bear the horizontal planes (forjados) of the intermediate floors are discontinuous. Besides, the solution of battlement is much simpler than that of Monforte with merlons of much less thickness, i.e. the plane predominates, and although it is arranged on the basis of brackets, it presents a continuous separation between the tower and the battlement perimeters, while in Monforte only empty voids are produced between the merlons.

These same characteristics (separation between perimeters and merlons of relatively little thickness with a predominance of the plane sensation over the three dimensional one) exist in the Tower of Vilalba which is also single and has an entrance of middle height. The modifications introduced in the conversion of the tower in Parador have permitted to extract much minor doctrines. Moreover the octogonal form of its tower leads to the disposition of two ribbed arches for the bundle. The finial is in this way embattled.

Later the finials of the fortress of Monterrei, a family to whom belonged the tower of Vilanova during the reconstruction, were studied. Overhanging finials of machicolation type, placed over the brackets and situated at a very little distance of their border, were found. The study of the Tower of Pontedeume that belonged to the Andrade family has given one more example of a machicolation finial bent on its perimeter. This discovery made us consider the machicolation finial as a widespread type since the examples are situated in the north and in the south of Galicia.

The visit to the Andrade family Castle in Cabañas, also known as the Castle de Nogueirosa, showed the application of many of the studied solutions. The castle belongs to a mixed typology with a dominant tower that from a distance gives the impression of an isolated tower. When getting closer the facades that delimit the castle are better seen at a closer perspective. The entrance to the tower is situated at a level a little higher than the one that unites the ramparts with it. The shape of the entrance void is similar to that of Vilanova. Moreover it presents a machicolation finial over brackets with the peen located a little backwards from the brackets, In the interior the tower has got a vault as a covering reinforced, in this case, by ribbed arches, while it isn't presented in Monforte. The horizontal planes (forjados) are plywooded over the continuous stone corbells to receive the wooden dormants.

After having realized these first studies the characteristics were systematized to compare them with those of many other fortifications and summarized in the following compendium.

Description of the Type

The study and the comparison of different fortifications have tried to formulate the building type by summing up the following characteristics:

—Location:
  —isolated (Doncos),
  —independent in an ensemble (Monforte, Castroverde),
  —linked with an ensemble (Pontedeume, Nogueirosa),
  —integrated in an ensemble (Monterrei, Pambre);
—Access to:
  —ground floor-secondary access (Doncos, Celas, Pontedeume
  —top floor:
    —from the ground (Monforte, Castroverde),
    —from another building:
      —ramparts (Nogueirosa, Narahio, Doiras),
      —palace (Pontedeume);

—Floor:
—rectangular (the great majority),
—other:
—octogonal (Vilalba),
—circular (Sarria);

—Vertical section:
—straight (Monforte, Vilalba),
—stepped-with Berms (Pontedeume);

—Number of superior floors/access:
—three (the majority),
—other (A Porqueira, 4);

—The use of the ground floor/access:
—pool (Monforte),
—prison (Pontedeume, O Bolo),
—former building (Vilanova),
—secret exit, tunnel (Narahio),
—excavated basements Doncos);

—Masonries:
—ashlar of granite (Narahio, Monforte, Parga, Friol Narla, Pambre),
—rubblework:
—granite with ashlar reinforcements (Nogueirosa),
—slate with granite ashlar (Vilalba, Doncos, Viana do Bolo),
—rubblework:
—granite (Miraz, Valdeorras),
—slate (Burón, Doncos, Doiras, Navia de Suarna);

—Horizontal planes (forjados):
—All wooden (the majority), supports over:
—stone corbels:
—continuous (Vilanova),
—unitary (Castroverde),
—embedded beams,
—Vaulted:
—roof (Torre de Andrade, Caldaloba),
—basement (O Bolo),
—roof and basement (Monforte);

—Stairs:
—In the space of the floor,
—Integrated in the walls partially or completely (Nogueirosa, superior level in Monforte);

—Character:
—Defensive (the majority),
—Palace type;

—Crown finials:
—Embattled:
—by placement:
—overhanging over the brackets (Vilalba),
—levelled (Castro de Ouro, Doncos, Doiras, Miraz, Narla),
—by the form:
—pointed (Narla Vimianzo, Miraz),
—rectangular (the majority),
—by the type:
—three dimensional (Monforte, Narla, Doiras),
—plane (Andrade, Castroverde);
—Machicolation:
—levelled (Xunqueira, Castro Caldelas),
—overhanging over the brackets (Monterrei),
—With reinforcements:
—fortification turrets (Monterrei, Castro Caldelas),
—bent machicolation (Pontedeume),
—circular machicolation (Pontedeume Vilamarin),
—With loopholes (Vilalba, Castro Caldelas),
—Without loopholes (the majority);

—Voids:
—Large windows:
—rectangular,
—arched,
—geminated,
—Loopholes (saeteras),
—Loopholes (aspilleras);

—Water discharge:
—Gorgoile,
—On a level;

—Peculiar elements:
—Coat of arms (Pontedeume, Narla),
—Sculptures (Vilalba),
—Toilets (Castroverde, Penas),
—Chimneys (Monforte, Vilalba, Nogueirosa, Penas).

With the help of this classification we briefly describe the towers which are situated near the tower under restoration beliving that their phisical characteristics would be more similar to the tower of Vilanova than to the others situated at a greater geographical distance.

Sande: Isolated on a rock. Granite ashlar. Rectangular floor and straight cross section. In ruins but not destroyed by «irmandiños».

Sandiás: Isolated on a rock. Granite ashlar. Rectangular floor and straight cross section. Three floors and a basement. Horizontal wooden planes (forjados) over isolated corbels. Superior brackets in corners and central part of each face. Only loopholes. Destroyed by «irmandiños», at present exists half of the tower.

Xinzo: Rock. In the interior of a precinct with attaching constructions. Rectangular floor and straight cross section, of ashlar granite and a very enclosed appearance —only loopholes, with vaulted flats and a basement thought for a pool. Lack of superior finial, but overhanging brackets over the perimeter are conserved.

Celme: Rubblework of granite. Rests of overhangimg brackets.

Milmanda: Castle in which there are no ruins of the Torre de Homenaje.

A Porqueira: Isolated, of rectangular floor and of straight cross section. Granite ashlar with rectangular voids, very narrow but bigger than the loopholes. Access at a certain height. Four floors above the access including it. Perimetric brackets over which rests of machicolation are observed. According to the historians it has maintained its original structure.

Monterrei: Was adapting its systems with the evolution of war techniques, because of which its image is changed too much in respect with what it was in the Middle Ages. Integrated fortress, two outstanding medieval towers: the Torre de las Damas and the Torre de Homenaje, both of them of square floor, straight cross section, granite ashlar with few large windows. The Torre de las Damas has got rests of attached edifications. It is finished with overhanging even machicolation over brackets. The Torre de Homenaje is isolated, with an entrance at a certain height reachable by a staircase lifted manually from the ramparts. Finished by overhanging machicolation over the brackets, reinforced by fortification turrets in the corners and in the centre of the faces.

Having realized this characterization of the type, that we can call a horizontal study in the time, other possible alterations and peculiarities of the tower of Vilanova may be supposed as a consequence of it:

— modification of the roof level: according to the comparative studies it would lie upon a wooden dormant supported by a stone continuous corbels of the last floor, with the destruction of the finial system of the tower;
— modification of the access system with the newly added door: the typological study led us to the hypothesis of the system of access to the tower from the perimetric façades like in Monterrei or Nogueirosa. The presence of stone corbels that surround the zone of the arched balcony of the same height, as the rampart could have, together with what seems to be the trace of an ancient staircase between these levels and what the lichen shows make us suspect that a system of access from the façades of the perimetric ramparts existed. However the scarcity of certain data and the great importance of the suffered alterations make us banish any temptation of reconstruction;
— the staircase introduced during the 1992–1993 restoration does not seem to correspond to the historical situation of these buildings, since the horizontal planes (forjados) were plywooding

their arrangement on different floors with the purpose of providing major rigidity to the ensemble and uniformizing the load that different walls were transmitting to the laying of foundations;

— the horizontal levels defined during the same restoration bring up doubts about the successfulness of its situation since there are traces in the masonries of other levels;

— referring to the same restoration, there are other disputable interventions: the opening of the vertical space that covers all the floors of the tower which is totally strange for this type of edification, the introduction of elements of vertical partitioning that does not permit a common space for each floor of the tower as well as the arrangement of a false ceiling that cuts the interior flarings of the voids.

However the adopted philosopy —not to deny the course of the history, and the little importance of the intervention lead us to propose tiny actions that will reduce the observed defects.

Description and Justification of Intervention

Acting in the historical area is always a problematic matter. The following aspects are summed up to the difficulties of any construction project itself: the undeniable presence of the history condensed in the stones of the place imposing some especially strict rules, the dysfunctions produced by the history for contemporary use when the formalization process owes to past circumstances that legates its phisical configuration, the necessity not to renounce the condition of contemporaneity that any piece of Architecture demands. One should not forget either the social sensitivity that an intervention awakes.

The intervention has been undertaken since the theory of the strata: each historical moment, as it would refer to geological times, superposes its action on the city and the building depositing itself over the precedents without interfering with them and at the same time being a visible element in the whole ensemble. In this sense the intervention deposits over the town as it were a carpet and like modern furniture in the buildings. The reversibility of the action is a prerequisite feature of the intervention in the patrimony.

The adequation of the introduced usages and the characteristics of the edification that supports them is imposed: the basic definition of the types of the action object —load structural walls, horizontal planes (forjados) and voids, which are carefully maintained and restored. Thus the spaces are defined and interpreted as containers in which the different usages are deposited carefully.

It has seemed to be appropriate to establish a correspondence between the tripartite character of the program and three differentiated fields of the preexistences —superior floor, ground floor and tower (Figure 1) in such a way that each part of the program is developed in one of them. The new necessary partitons are arranged as if furniture is being treated, avoiding the contact between the additions and the existing walls, every moment evaluating the contrast of materials techniques and thicknesses, contrast that leads to the limits using dry construction techniques.

When dealing with three independent elements, their relation to the consecutive presentation of their accesses is committed: the ancient houses with an access from the square support the more traditional use —the restoration; the access to the Centro Comarcal— the modern usage, is realized by an added element which is a reinterpretation of the «patines del pueblo». The presentation of the accesses to the tower culminates as an emblematic element. The three historical buildings have conserved their old accesses as much as possible adjusting themselves to permit the functioning of the three big parts that form the program —cafeteria, expositon and offices, facilitating its autonomous use.

The segregation between the top and ground floors of the building takes into account analyzed building typology, with the ground and top floors of very different meanings and uses. The modification is expressed in a roof that integrates the two houses in only one three dimentional space, facilitating its unity. For that reason the elevation of the cornise height of the two houses is to be accepted to define a unique line that will be resolved by an entrance of a filtered light: a shade in the elevation. The intervention pretends to use materials that in the local construction experience have been proved to be valid: the tile on the roofs, the local traditon of construction in wood, stone, glass and of course the magnificent use of the metalic façades within the frame of the

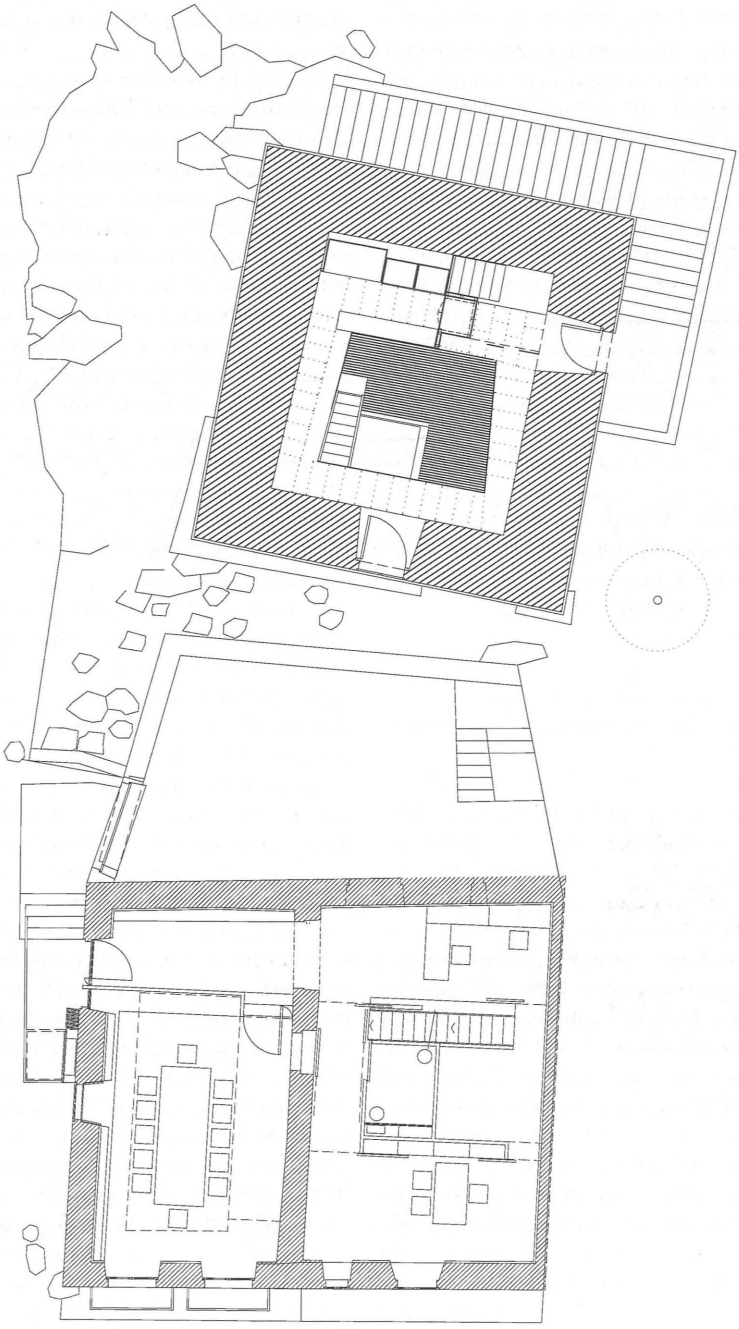


Figure 1
Centro Comarcal «Terras de Celanova». Intervention floor. Executed proposal. Freire, Vazquez and Macias —the architects

popular tradition that can be enjoyed when walking in the town.

The urbanization is conceived as a carpet extended over the place. A flagstone pavement reminds the layout of the rampart of the town. The whole urbanization is created from this element and the definition of the historical environments: local pebbles among the strips of granite flagstones show that formerly it was a yard of arms with the rocky outcrops integrating into the pavement; a paving of granite pieces of 6 × 6 covers the old access to the tower which tangetially passes defining independent, adjacent spaces: the storehouse space, the space of access to the Centre, the bastion space. In this space succession we try to facilitate the organization of open-air sculpture expositions. For this purpose some embedded ilumination points are installed by inserting them in the pavement or in other elements permitting a minimum illumination, two more double points are added that will illuminate the volume of the tower diagonally configuring it also as a nocturnal reference.

Intervention Proposals Based on the Typological Analyses of the Late Medieval Towers

The actions in the tower are planned in the light of the historical memory and the realized typological investigations. Initially it is assumed that the historical flux is a fact, without denying the different transformations that history has introduced in the building, adapting this to the new requirements, that are now demanded, meanwhile the defects that complicate the comprehension of the building and make the other characteristics that could remain unnoticed by the visitor, are corrected. From this point of view, the interventions that have been realiazed in the last century are assumed to be unsuccessful but our intention is not a historical retrospective. Our purpose is surely to recuperate signes of the lost identity, as for example the belonging of the tower to a fortified ensemble revealing the castle rampart layout on the urbanization pavement, the ruins of the tower destroyed by the «irmandiños», the layout of which is seen on the pavement of the access floor. Another purpose is to recuperate fortress data reintroducing the crowning elements and the perimetric walk together with the merlons, or the functioning of the old access.

That is why one of the first adopted decisions was to reconstruct the roof. Given the fact of the closeness between Vilanova and the fortification of Monterrei, also the fact of Vilanova belonging to this family at the time of the possible reconstruction and the date corresponding to it, the finial crown adopted in the project is of the machicolation type. For the clear differentiation of the original from the not original one, it was decided to build it of wooden elements. Besides, considering the stability of the stone corbels uncertain, it was decided to use an auxiliary metalic structure to guarantee the structural security. In this way the reversibility is entirely assured, the top can be easily eliminated, a produced popular response taken as a prerequisite condition, as well as the reference to the origines of the wooden fortifications, at the time when the continuous finial floating over the bracket is obtained.

In none of the analyzed towers a setback that appears in Vilanova is observed. Its uniqueness together with: the study of the bibliography, the importance of the interior tower, amputated wall scars that are observed on the west façade, (a scar that possibly exists though hidden on the west side, because of the addition of the staircase in the 19th century) the stone corbels of middle height in its perimeter focused the study interest upon the towers linked with defensive precincts conformed a mixed image between the Castle and the single tower.

From this kind of studies came up a suspicion (for us a conviction) that, given the fact that the tower belonged to a fortified ensemble as the archeological investigations show, the entrance to the tower was realized by ascending from the rampart to a superior level that was reached by means of exterior perimetric stairs, supported by stone corbels that are still visible, similar to the access of D. Sancho de Monterrei. The fact that the present entrance to the tower was built in XIX century (according to the archeological excavations data) corroborates this suppositions. However, the present attitude not to negate the different transformations that the buildings have undergone throughout the history, like the lack of more data and the complete disappearance of the façades of the ramparts which would support the access, have led to discarding a decisive action upon

the subject, limiting the intervention, lightly marking this possibility together with balcony protection design blocked up at the front and swooping at the sides where the rampart walk would pass.

The studies done during the realization of the project and the course of the work permitted to ascertain the Vilanova ramparts and to match the layout supposed by Eguileta(1994) and to nominate two towers of the town defensive system, one of which was found in the interior of the rehabilitated houses, Figure 2. The project includes the layout of the ramparts by placing a pavement where a wall is supposed to have been. Besides the disposition of a row of relocated willows of the square, pretends to delimit the space proportioning a scale similar to that of the arms yard, the perception of which is strengthened by partially placing a pebble pavement.

The same didactic spirit with which the exterior intervention faces up is maintained in the interior. Thus the recuperation of the ruins of the ancient tower is undertaken. Its interior is made accessible by means of one- flight staircase of the type detected in the studies. While its plan of the ground floor differs by a granite paving, teak wood is used for the rest of the floor.

The previous intervention impeded the perception of a unique space for each of the tower floor by placing an acid treated glass screen that closed a number of halls on each floor; by attaching installations to the tower walls and damaging them by the connection tubes sistem and hiding the configuration of the voids by false ceilings which impeded to see its constructive resolution. It was decided to eliminate all these interventions by placing the installation on the floor and on the ceilings, substituting the false ceilings and dismounting the glass screens to amplify the unitary character of the floor. The position of the two horisontal planes (forjados) placed in the previous intervention has been preserved, as well as the layout of the staircase, and as we are not sure about its correspondence to the original one and we have not got enough data for a reliable action to give it an image more appropriate to the original building, a facing of dark wood has been used.

In the superior level under the covering, two continuous stone corbels can be observed, the mission of which is the previously mentioned one, i.e. to support a horizontal plane (forjado), possibly that of the covering. Its position, which is not connected with it, indicates an itervention of probably the past century that has drastically modified the levels of the tower. One of the corbels is interrupted by a vertical void which, judging by its fitting, was created later than the building of the tower. The impossibility of correcting the levels, because of the lack of data, leads to accepting them and giving a solution —illumination of the stone corbels hidden by some boards that pretends to remind the meaning of those corbels.

Finally the slate soldier, extraneous to the place, was removed to realize an inverted roof with a finishing of local granite tiles.

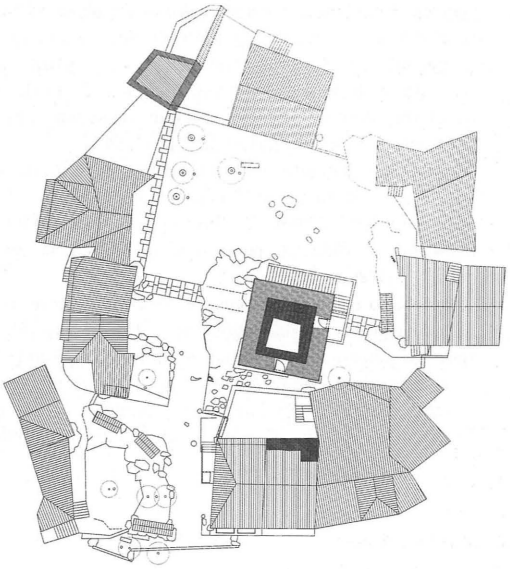


Figure 2
Fortifications ground in the proximity of the Tower of Vilanova

Notes

1. At present there is the book of Varela (1999), with a minimum fotographic report and a brief commentary about numerous galician towers, that can serve as a basis of support for the project maker.
   At the national level, Sotelo (1999) has six galician castles.
2. The rebellion of the «irmandiños» (hermandinos in spanish) was a turn against the knights and the lords of the

Galician Kingdom as a consequence of the abuse of the latter that took place during 1466–69. See for example *«irmandiños»* in Silveiro Cañada ed. 1974 vol. XVIII.

3. As a proof there is a document of March 2, 1481 in which the abbot of Celanova sanctions those who were guilty of the destruction (Eguileta 1994, 514).
   Anno de mill e quatroçentos e oytenta e un anos, dous dias do mes de março en Celanova (. . .) diso (. . .) que o dito señor abade lles fazera pagar çento e vinte maravedis a cada un pera torre de Villanova que derribou a Yrmandade.
4. Cristobal de Rojas introduces the new solutions in the «Teoria y practica de la fortificación», 1582. From 1587 starts the construction of the castles of San Felipe and of San Anton in the port of A Coruña according to the new methods (Varela 1999). The previous author realizes the fortification of the Ciudadela de Cadiz in 1598 (Soraluce, 1981).

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Catalan methods for construction in Sardinia: The use of «abeurador» in stone masonry

Gabriela Frulio

Sardinia got on to the Spanish political and cultural influence during the14th century, from then a real migration of people began towards the captured towns or the free-towns. Such people was employed in different activities, there was specially traders and craftsmen and masons with them.

The considerable cultural contribution was tightly connected with the technical applications, so that some rules of the masonry and some particular construction methods was implied in the change of taste and style. During the following centuries native people appropriated mason-craft or builder-craft gradually but in complete and fully aware way.

The studies and the researches about this period of the Sardinian history concerning specially political, economical or social influence between the island and Spain; there are also some studies about history of art (architecture, sculpture, painting), but the history of connection in method for construction and the history of building workmen migration are not investigated, yet.

The goal of this research is to prove as studying constructions' methods is possible to identify the source of building workmen, in order to define groups of structures that are thought or built by the same rules. To identify groups of structures in a geographical context wider then source context, it means to connect researches also with the neighbouring constructive examples. It will have the purpose to define a classification method for the constructive, behaviour and damage model.

About archives and historical documents: studying Sardinian bookkeeping documents of the 15th–17th century written in Catalan language, it's noticed a particular affinity of the technical-constructive terminology whit the same terminology coming from Baleares Islands and again in use. In fact it is noticed the affinities that joins Palma of Mallorca with Sardinia about the most utilised material of stone masonry: stone of «mares»/ »massacà» (same kind of

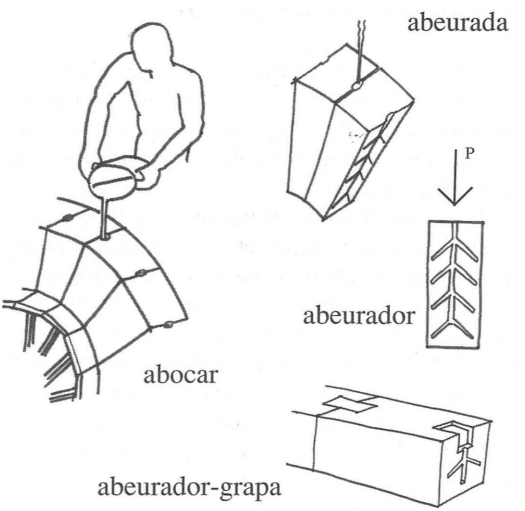


Figure 1
Operation of «abeurador»

sedimentary stone). It has caused the same technique in cutting of stones and in the correspondent pieces' dimensions of blocks.

About buildings and structures: to analyse the use of the «abeurador» as a method for construction and assembling of arches, of strain blocks and of stereotomyc elements, that is diffused in Sardinia and in Palma.

Goal of the research

The present research is just a piece of a larger study about historical methods of construction in Sardinia during the Spanish influence. The goal is to create a data base in order to connect data resulted from studying archives' sources with data belonged history of construction's methods. The data base has the purpose to recognize each methods as special and particular one: 1st belonged to a certain historical period (then useful to identify the age of the building or of one of its parts); 2nd belonged to a particular cultural circle (in order to identify the workmen or their place of origin); 3rd belonged to a specific static and structural meaning (then useful to restoration works).

An example of catalan method of construction: the «abeurador»

The object of this research is the «abeurador», a methods of constructions that belong to Catalan countries and tightly to the cultural milieu of Baleares Islands, that are near Sardinia in historical and geographic meaning.

The «abeurador» or «beurador» is a little carved canal in the stone block exactly on the plain of laying joint. It must be filled of special mortar («beurada») and assembled with a symmetric one. When the mortar is wiped the «abeurador» makes use of joint nerve between the blocks. From the outside the result is a structure that seems built without joint of mortar; in fact it is specially made use for arches, pillars or columns with mouldings, special blocks or particular pieces of the masonry, just when the mortar joint must be invisible. The carved canal has different proceeding, it depends not by the block's shape but by the block's function when it is assembled in to the wall. In moulded blocks for the arches the carved canal has shape of arrow or fish thorn.

It is instead not used for generic walls, in order that the masonry's rules with stonework's sheathing are founded on different criteria and are not object of this part of research.

This method for construction is used specially on buildings as gothic-catalan architecture, for example in Sardinia on portal with stone arch. Such arch called «adovellado» is built with long trapezoidal stone-blocks arranged like a fan apparently without mortar, but with the carved canal on the interior side. The mason filled the carved pouring the «abeurada» by the mouth of the jug.

By means of studying and comparing archives and historical documents (and also by other parameters) it's possible to retain that this method has came in Sardinia from the Baleares' construction culture.

In a Catalan dictionary of construction method (Diccionari de l'Art y dels Oficis de la Costruccio, Mallorca 1988) the word «abeurador» means: furrow made from stone-cutter or mason on the construction blocks, in order that the «abaurada» (kind of mortar) could be poured inside and also in order that it is used, fool of mortar, like a joint nerve in to the stone-blocks.

The method is effective for stone-blocks of arches («abeurador» as an arrow) or pillar or column (simple

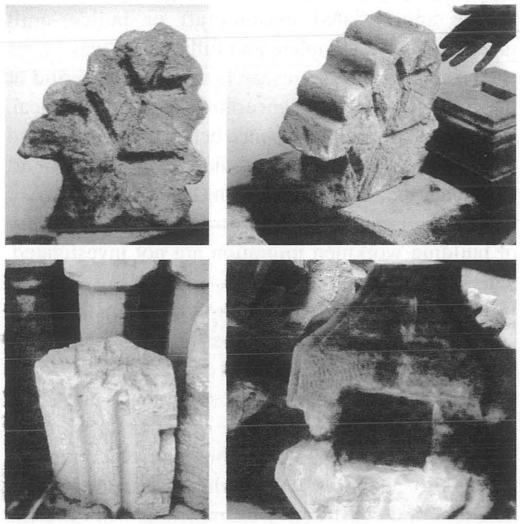


Figure 2
«Abeuradors» in Cathedral of Palma of Mallorca

«abeurador» or just with one or two transversal carved canal). For example the furrows found on stone-blocks of the Majorca's cathedral, during restoration works, are simple «abeurador» carved on moulded stone pieces, got on to the structure as blocs without mortar. In Sardinia also is possible to find simple «abaurador» used in pillar's block, like the carved one in the stone-block of the circular pillar holding the umbrella-vault in the Tramariglio's tower of Alghero; nevertheless, as we can see at present, there are specially arrows for arches.

The arrow served a purpose to raise the distribution surface of the inner reinforcement. But it's necessary to reflect upon the direction and the way of the

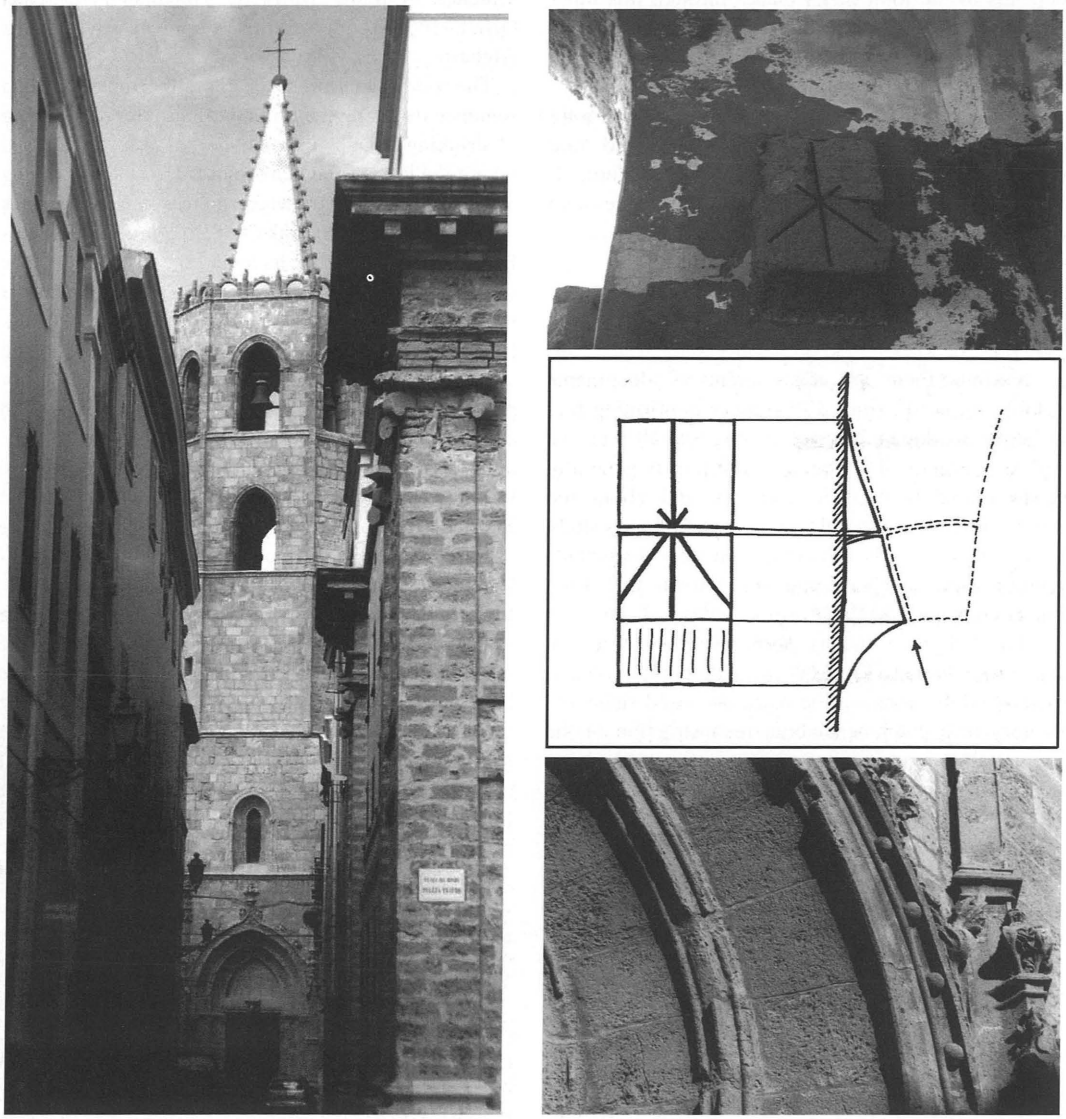


Figure 3
Remain of arch with «abeurador» in the bell tower of Alghero's Cathedral

arrow's wings or of the transversal carved canal. They are always in agreement with the mortar's possibility to flow down throw all the carved-canal, in the opposite the mortar couldn't fill the furrow up. In the mean-time the structural meaning of the stone-block is that the arrow's wings must be carved in the opposite direction of the compression strain. Then, for example, the resistance of the arch's system also depends to the joint of its pieces through this inner armour of mortar; in fact the arrow's direction is on the opposite of the strain. The joint react as a friction strain opposite to the sliding of the blocks.

So it's possible building arches that seem joint without mortar, but have inside a solid and collaborating armour to contrast the vertical force. It is the same building with stereotomyc pieces and using the carved canal as an aid.

Archives and historical documents

In Sardinia there are many archives' documents datable from 14th since 17th century confirming that building workmen belong in linguistically to the Baleares islands. The linguistic affinity is generally about materials used in masonry and about the dimension of the stone-blocks. For example lets study some catalan words in comparison with documents coming from Alghero, the small town that keep ancient catalan language since today. «Cantò» in catalan language means corner, corner-stone, in Alghero it means stone-block with perfect corner, with fixed dimensions; the word was used since 14th century in a parchment about reconstruction of the town-walls. In Minorca «cantò» means block of «marès»-stone (local sandstone) cut as parallelepiped with fixed dimension, similar to the blocks from Alghero. And again: «pessa» in catalan construction's culture is a big stone-block proceeded from the cave, like approximately in Alghero. The same we can discover about «mitja», «quadros» and others. Plus the sandstone from Majorca and the one from Alghero («massacà»-stone) have the same nature and structural characteristics and both are easy to take out and to carve.

In the language of Majorca the word «abaurador» or «abeurada» is often used, yet but in Sardinia they are completely forgotten. Then it's evident the importance to studying documents comparing them with material traces on buildings, in order to identify the common cultural circle and first of all the origin's place of the workmen.

Portar la calsina en lo moll o beurador

Lets try to translate one piece from this historical sources: «Portar la calsina en lo moll o beurador», a sentence from the Tarifa de Traballadors de cada Offici, 1653–1658, kept in Historical Archives of Alghero.

The first hypothesis for literally translating the sentence is: taking the lime to the quay or to the place of drinking-trough. It could be possible to think of taking the lime to the quay in order to sell it or taking to the drinking-trough, where there was large quantity of water, in order to slake the lime in to the basins. But the sentence could have an other meaning in the translation, yet: putting the lime in to the mortar, as mollifying the quicklime, or in to the «beurada» (special kind of mortar), or taking the lime to the «beurador» (the worker who makes the «beurada») or putting the lime in to the «abeurador» (the carved canal).

There are two reasons for being inclined to believe that the last interpretation is the right one. In fact Sardinia is a country rich in limestone, and the lime generally had a local production, quarries and lime-kiln was largely located in many areas of island, usually in the country place near the towns or villages. Then instead of meaning to board in the quay the lime and to sell it somewhere, it could be better translate the sentence as mollifying the quicklime («moll»). The second reason, about the translation of the word «abeurador» as a place of drinking-trough, concern that the basins to slake the lime was generally located near the building yard or near the lime-kilns, then (following the tale of the document) is not understandable the necessity to take the lime of the kilns and bring it to the basin located near the drinking-trough, after from there to the building place.

The ground of this doubt during the translation is sure having forgotten a construction method; this is just one exempla of the possibility to find mistakes studying an historical document without keeping contact with the material argument of the text.

Occasions of discovering

It is generally difficult discovering the presence of «abeuradors» in buildings, for the reason that they are inside the wall's structure. In Sardinia we usually find some of this arrows or furrows only in external face of the wall, when it is built whit salvage material or loose blocks belonged to a preceding structure. Then they have a casual disposition in the facade's composition. Unusually instead they could be found in their original position on a building in ruin condition.

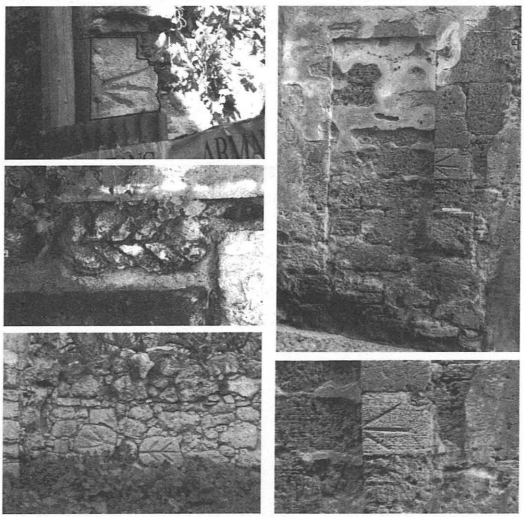


Figure 4
Occasion of discovering in Alghero

Temporary catalogue of discovering

This is a temporary catalogue of «abeuradors»' discovering; naturally the continuation of this research and the bringing up to date of data-base will sure give more and more information about them and discovering.

Alghero found 11 arrows in structure built with blocks belonged to a preceding structure (boundary walls, closed holes, structure rebuilt after the second world war), 1 arrow in original position (impost of arch in to the bell tower of cathedral), some carved canal in original position (circular pillar). One of this arrows is notable for the number of wings.

Sassari: found 1 arrows and 1 carved canal in walls built with material taken of a preceding masonry (structure of 17th century of S. Maria of Bethlem, Cathedral).
Monteleone Roccadoria: 1 arrow in not original position (boundary wall).

Bolotana: 3 arrows in the same building in casual position on the walls (structure of 16th century of S. Bachisio).

Ploaghe: 1 arrow in not original position.

Cagliari: 15 arrows and 2 furrows with transversal canal in structure built with blocks belonged to a preceding structure (boundary walls, closed holes, structure rebuilt after the second world war, cathedral), 2 arrow in original position and in the same structure (2 blocks of a double arch «adovellado» in a ruin wall). There are a lot of different kind of carved canal or arrows.

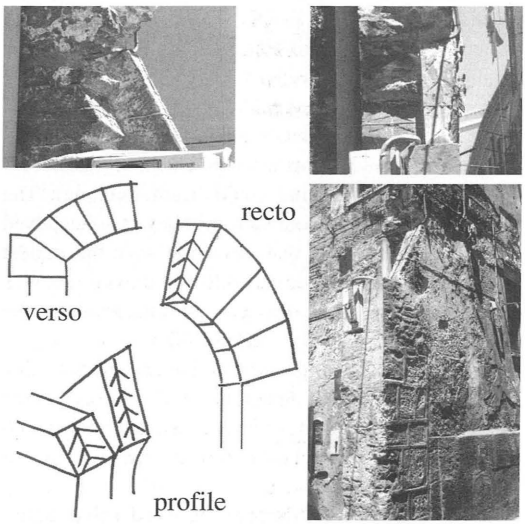


Figure 5
Double arch «adovellado» (recto) and «regràs fals» (verso) with «abeuradors» carved on two blocks, in Cagliari

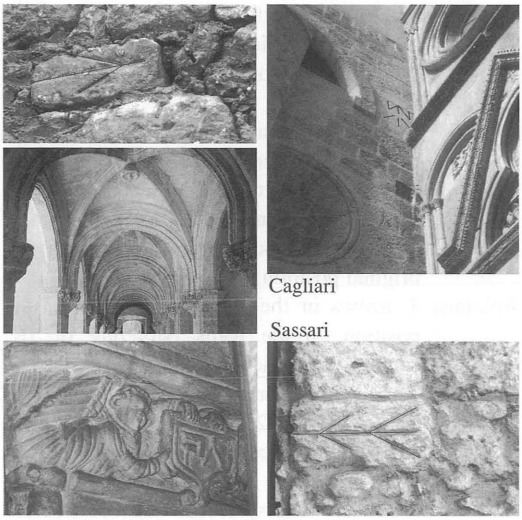


Figure 6
Occasion of discovering in Cagliari and in Sassari

Dimension of recovered blocks and relation with the carved canal

Studying «abeuradors» in recovered blocks it's possible notice some constants. The furrows, carved arrows or carved canals, usually hold all the side's surface of the block, either length or width. There are two kinds of arrows, with simple wings and with multiple wings. For example a block recovered in Alghero has even five wings in the same arrow. In the group of simple arrows there are two different kinds again: the most common is the «abeurador» with open wings touching the block's corner on 45° (this kind could begin multiple). The second is a simpler «abeurador» with a very long carved canal and little wings that never are over the middle third. The blocks have usually different dimension, but a fix width of 25–35 cm, then it is easy understanding the dimensional relation of the «abeuradors».

This is a very important notice in order to not confuse this furrows with job-work's marks by the «picapedrers» that sometimes are like arrows but with less dimensions in relation to the block. An other important point of you is about studies concerning width and deep of the carved canal. Usually it shows a section about 1 or 2 cm, and maybe it depends on structural assignment of the block and on haw much mortar it needed.

Features of the mortar nerve

In to the carved canal must run the «abeurada», kind of mortar made with lime, water, not much sand and with a good mixing, in order to be flowing. In Sardinia there are not found rests of this mortar inside the carved canals yet, but it depends on occasion of discovering.

Then it is just possible to believe that sardinian mortar for «abeurador» was a kind of mortar similar to the one found in Catalunya inside the same carved canals. About the laying of the blocks: in case of arches construction the flowing of the mortar happened probably just when the faces of the two blocks was placed side by side, then from the top of the framework. On the opposite the flowing mortar could fall down.

Application and first results from the comparative study of the data base

About bell tower of the Alghero's cathedral: the arrow found in a impost of arch in to the bell tower is in a intermediate level between two floors. It means

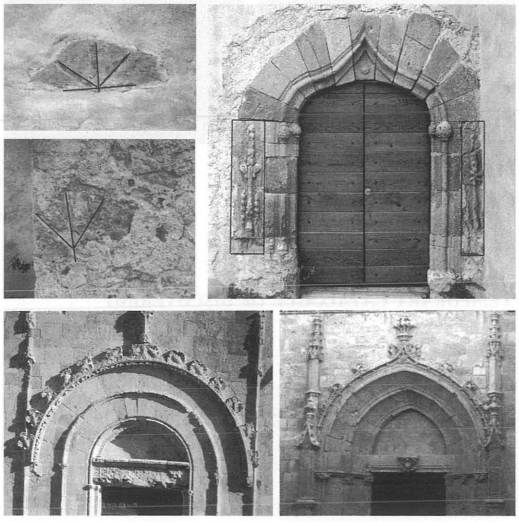


Figure 7
Reconstruction's hypothesis of an «adovellado» arch with spires, belonged the first building phase of the church of San Bachisio in Bolotana. Below two exempla of Catalan arches with spires in Pozzomaggiore and in Alghero

that in the first project the floors must be unlike actually and that the bell tower had more than one building phase. A second hypothesis is that the impost of arch is the only evidence of a project changed during works. Sure, without the knowledge of the arrow's meaning it would be difficult to handstand the presence of the arch.

About the church of San Bachisio in Bolotana: it's known that the church had two building phases, but the document notify just about the second one (16th century). Then it's unknown the construction date of the first building. Studying the architectonic structure same blocks from the first phase are recognisable on the walls having the carved canal as an arrow, plus there are two spires carved in long blocks on non correct position. Adding this parts it could be possible rebuild an «adovellado» arch with carved spires on the sides, like same arches in sardinian churches dated 15th century. Then it's almost possible give a chronology to a part belonged the first building phase.

The same meanings are possible in other cases, for example in Cagliari or in Sassari, using the knowledge of this method of construction, as an instrument useful to date or to understand some part of a building, but never leaving the complex study of a whole building.

From a technical point of view it's easy understanding the importance of «abeurador» during restoration works specially on restoration of arches that seems built without joint of mortar. That's in order to avoid a mistake scarifying the blocks and making a large joint of mortar or reinforcing a structure that has inside a mortar bracket, yet.

The evolution of traditional types of building foundation prior to the first industrial revolution

Ana María García Gamallo

The aim of this paper is to describe the chronological evolution of the traditional types of building foundation used in buildings constructed within the borders of the former European provinces of the Roman Empire, during the period of time spanning from the appearance of the first of these types of foundations up to the dawn of the first Industrial Revolution.

With this aim in mind, archaeological, historical and bibliographical information related to sizing and building processes used in the construction of foundations, both shallow and deep, over the period studied, has been critically gathered and ordered.

Both the geographical scope and the time span chosen are very wide, because given the scarceness of doctrine on these matters, it is intended to lay down a general approach and open up the way for future and more in-depth investigation.

Antecedents of shallow foundations

Before going into the study of the chronological evolution of shallow foundations, it would seem convenient to carry out a brief critical analysis of the different prototypes and of how they came into being, because, as will be seen, the causes behind their origins had a huge influence on their later evolution.

Prototypes of footings

The antecedents and/or prototypes of footings appear to be much more related to constructional and compositional matters than to specifically geotechnical ones. These prototypes are the following:

— Of isolated pad foundations: the embedded block of stone and the stone pedestal.
— Of strip foundations: the trench foundation under wall.

The origin of the embedded block of stone coincides with the erection of the first megalithic constructions.

Towards the year 4000 B.C., European man already knows how to drive a tree trunk into the ground. But knowledge of this technique does not enable him to embed a great block of stone, of several tonnes in weight, so that it remains upright.

The solution given to this specifically constructive problem is making an excavation that allows the position of the stone block to be changed, tipping it from the horizontal to the vertical position. (See figure 1).

Once this problem had been solved, it was very likely realized that varying the depth of the excavation made it possible to achieve an approximately horizontal plane at the top of the building, even though

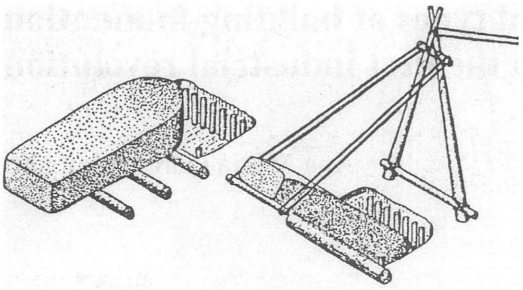


Figure 1
Erection of menhirs (Atkinson 1956)

stone blocks of different heights had been used. Through this discovery, excavation took on a compositional function, closely linked to the origin of post-and-lintel architecture.

The origin of the stone pedestal, on the other hand, coincides with the appearance of the first buildings using true columns (in stone, timber or brick).

The great typological variety of these pedestals and their appearance in geographical regions far apart do not enable any relation between their use and the quality of the soil to be drawn. (See figure 2).

Moreover, it seems that these pedestals were built with no mechanical purpose in mind, and if they did have such a purpose, they were not well-resolved, because in most cases, the small surface area of their bases and their insufficient depth do not allow any mechanical function to be fulfilled by the stone: neither the spreading of loads nor the transmission of loads to the ground.

However, these pedestals did allow the position of columns to be fixed, and the bases and tops of the columns to be perfectly aligned in horizontal planes. So they did in fact carry out constructional and compositional functions.

Something similar happened with the prototype of the trench foundation under wall. In fact the first examples of walls built in an excavation form part of buildings resting on rocky ground, in which, from the mechanical and geotechnical point of view, there was little need to build footing foundations below the walls.

Besides, these first masonry strip foundations are elements completely indistinguishable from the structure they bear, for which reason it does not seem they were built with the intention of serving as

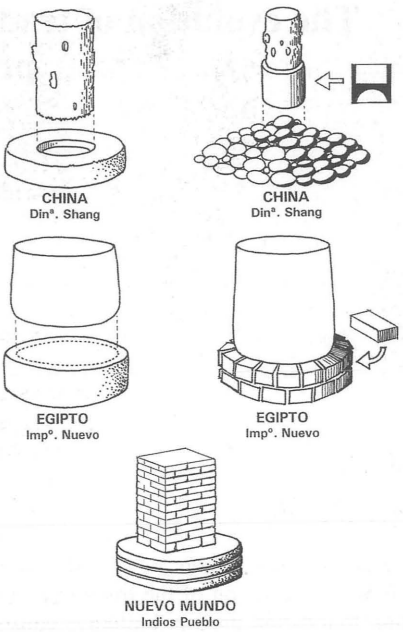


Figure 2
Types of pedestal

elements for spreading or transmitting loads to the ground.

However, there is no doubting that the excavations these walls were built on, facilitated the process of setting them out and levelling them extraordinarily, for which reason the origin of these excavations would seem to be related more to constructional and compositional needs than to mechanical ones.

Prototypes of raft foundations

Without a doubt, the antecedents and/or prototypes of raft foundations are elevated plinths, whose origin would appear to be strictly compositional. As a matter of fact, most authors agree that these artificial topographies were used exclusively to emphasize the importance of the building atop them.

It seems likely that this compositional, and non-mechanical, origin should influence the method of construction used for these plinths, insofar as real stone or brick masonry was not used in the process,

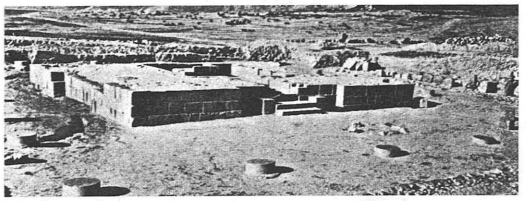


Figure 3
Stone plinth in Altinpepe (Özgüc 1966)

but instead only the products resulting directly from earth movements for site preparation.

But, at least in those plinths which have survived to our day, these materials were not simply dumped but carefully placed and treated so that they could work as a real structure and perform mechanical functions.

So it seems likely that plinths evolved from their originally purely compositional function to become real foundation structures, in this case raft foundations. Proof is found in that towards 800 B.C. the first plinths with real stone masonry were built. (See figure 3).

Prototypes of timber grillages

The antecedents and/or prototypes of timber grillages appear to be the plinths made from logs in primitive lakeside dwellings in the danubian region, belonging to the Neolithic period. As a matter of fact, it is from this time onwards that Man carries out the first attempts at improving the quality of his living spaces, which allow him to prolong his stay at the chosen settlement.

In those places where timber was readily available and the ground was very soft and wet (boglands), the timber plinth provided a certain degree of insulation against the dampness of the ground and some kind of reinforcement which made the floor of the dwelling fit for walking on.

In the beginning, these plinths did not perform any function related to resistance, as they are completely independent of the vertical elements which hold the dwelling up. But they evolved and, towards 3000 B.C., they became plinths of timber grillage supporting vertical elements, placed directly on the ground or built over piles, as in the case of lakedwellings. (See figure 4).

So, starting from a modestly utilitarian purpose, log plinths evolve into real foundation structures, which, in contrast to the rest of the prototypes of shallow foundations, do appear to be closely linked to the geotechnical characteristics of the ground, and in particular with those of soft grounds, in contact with water.

Chronological evolution of shallow foundations

Within the borders of the former European provinces of the Roman Empire, during the period of time studied in this paper, shallow foundations are almost always resolved with footings, and only exceptionally with raft foundations or timber grillages.

In these lines, we are only going to deal with the evolution of footings, because the lack of true raft foundations makes it hard to detect any kind of evolution at all, and because the timber grillages built up to the first Industrial Revolution do not display any real signs of evolution with respect to those employed in primitive lakedwellings, but simply become widespread, especially after the Middle Ages, when they began to be used as the base for footings on very soft grounds, in contact with water.

Ancient Greek architecture provides several important milestones in the evolution of footings, amongst which the following are worth a mention:

— The construction of footings completely distinct from the structure they bear.
— The occasional use of projecting and tapered section foundations.
— The introduction of bracing between footings.

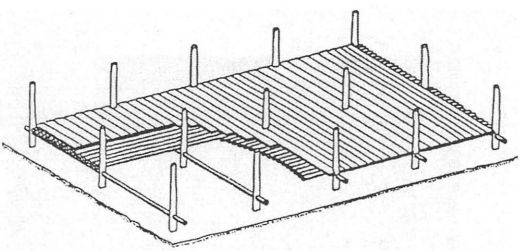


Figure 4
Lakedwellings belonging to the third phase of settlement at the archaeological site in Le Weier (Pétrequin 1984)

The most commonly used footings are strip foundations, usually built with a rectangular cross-section with no projection and resting directly on bedrock. (See figure 5).

Footings with projections or those with tapered cross-sections are only very rarely used, when, on excavating the foundations for singular buildings the bedrock does not appear at the expected depth. (See figure 5, again).

This cross-section, decreasing in width towards the foot of the wall, may have arisen due to economic reasons. But the widening of the foundation towards its base reveals a clearly mechanical intention and enables us to say that the Ancient Greeks were intuitively aware of the distribution of loads across a surface.

Moreover, there is no doubt that the use of these tapered cross-sections made it necessary to plan the dimensions of the foundation prior to its construction. What remains less clear is whether the dimensions were calculated according to the width of the element supported or according to the depth excavated to establish the footing's plane of support.

Tied footings appear in the Hellenistic period and are the culmination of a long process of struggling against the effects caused by earthquakes on Greek buildings.

Towards the year 800 B.C., the greeks are already aware of the fact that the horizontal direction is the most unfavourable component of seismic movements. The first attempts made to tie the building fabric through the insertion of logs and metallic cramps, from this moment onwards, bear witness to this. These solutions are followed, in the Classical period, by full bracing of the structure and transitional elements between it and the foundations (footings known as orthostatae).

So it does not seem strange that after all these experiences, the greeks should also try using ties in foundations, in one or both of the main directions. In fact, in some examples (temple of Apollo in Didyma), these ties form true load-bearing stone lattices beneath the buildings.

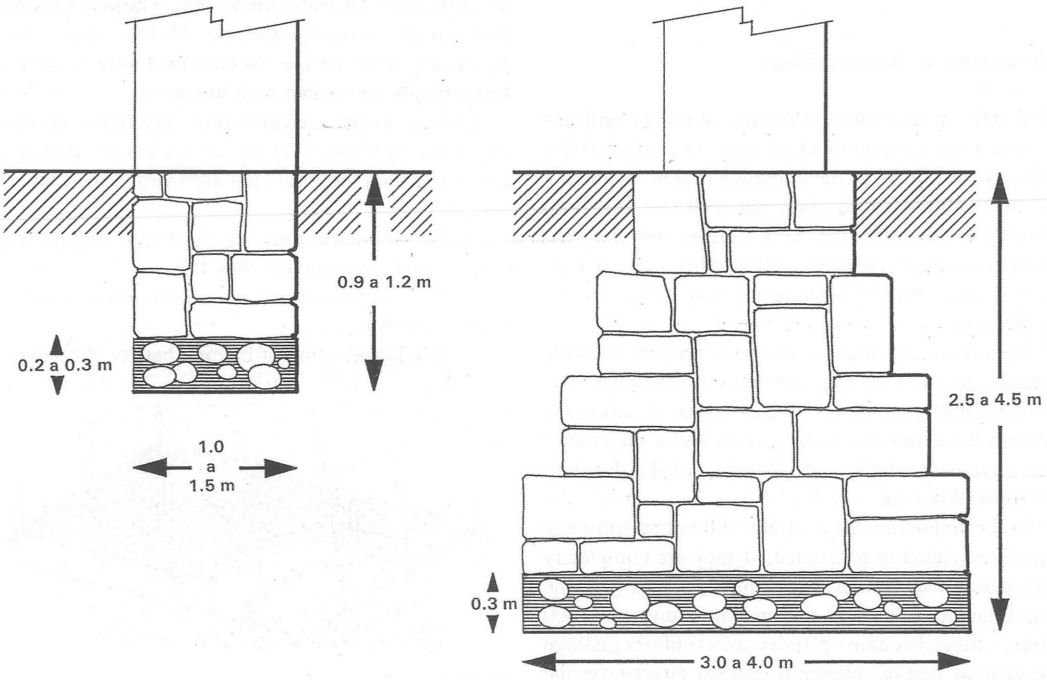


Figure 5
Strip foundations in Ancient Greek architecture

In Roman architecture, footings are already usually built with projections and a great variety of cross-sections. But it seems there was no rule for determining the size of the footings, because in the different examples, all the projections are different too, and because according to the translator Ortiz Sanz (1787), although Vitruvius *«orders that foundations be given greater width than walls above ground level»* he never defines the magnitude of that width, *«leaving it to the architect's discretion»*.

However, it seems likely that the Romans sized their foundations according to the loads to be born, and the load-bearing characteristics of the ground, at least qualitatively. In fact, Vitruvius himself (Book I, Chapter V) points out that the projection *«should be in relation to the quality and the magnitude of the building»*. And the foundations of the many notable buildings which have survived to this day show that the Romans paid heed to this recommendation, and also to the one contained in Chapter IX of that same Book I, in which Vitruvius remarks on the need to excavate the foundations until *«a solid bottom»* be found, and even to deepen further *«within it, as much as is necessary in relation to the importance of the construction»*. The foundations of Roman buildings destined for defensive purposes provide numerous examples.

But in the regions of northern Italy and Gaul, the Romans did not find that *«solid bottom»* at a reasonable depth, but instead very soft and wet soils, in great depths. This unfavourable circumstance led to a new constructional technique, which became widespread later throughout all the provinces of the Empire, remaining in use until well into the 19th century.

This new technique involved the construction of footings on soil improved by driving stakes into it, at very close intervals. (See figure 6).

It should come as no surprise that this solution should have become widespread because it is one of the greatest successes over the whole of the period studied in this paper. By driving stakes into the soil, three objectives were achieved: first, compacting the soil; second, inserting a material of higher resistance into the soft ground; and third, increasing the depth of the foundation's plane of support, all three of which improved the load-bearing capacity of the ground noticeably. And all these improvements were achieved without the need for excavating, something which was especially interesting where water was present.

Judging by Vitruvius (Book II, Chapter IX), the use of posts driven into the ground in order to compact it may have originated in Ravenna, a city with old timber buildings resting on piles, in which it seems very likely that the first masonry constructions were built on the remains of primitive buildings, that is to say on the timber posts driven into the ground to support the old pile-dwellings.

When faced with the problem of supporting new buildings on this type of ground, the solution consisting of extracting the old piles and then excavating trenches in the mire was obviously of much greater difficulty and far superior cost to that of resting directly on the remains of former constructions. So the most likely thing was that the builders of Ravenna, in the same way as builders of all times, adopted the simplest and most economic solution. And seeing their success, this same solution must have been tried out at other lakeside locations, but this time newly settled, where as a phase prior to construction of the buildings, stakes were driven into the soil, on top of which the foundations proper were then laid. Some authors, such as Fleming (1985), state that this procedure was followed in Venice, though at a later date.

Another event of the Roman era which also has a great repercussion on all later construction of foo-

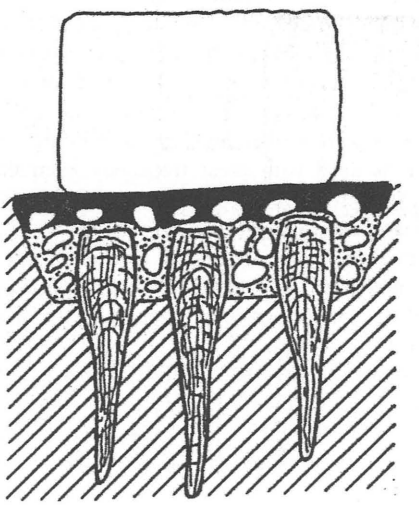


Figure 6
Roman foundations in «La Patonnière», Paulnay, Lower Berry, France (Kérisel 1985)

tings, is the introduction of a certain kind of plain concrete, made on-site with mortar and stones for foundation structures.

The earliest of these structures were used for economic reasons, in the city of Rome, when it was necessary to build foundations of great depth in section. But the advantages of these concrete structures (significant saving in both materials and labour) as compared to those made of stone or brick, led to their being used systematically at later stages.

From the fall of the Roman Empire to aproximatly the 15th century, there were not many new developments in foundations, because the shortage of resources characteristic of the Middle Ages did not allow large building projects to be undertaken until well into the 11th century, and once this stage had been reached, it was only using acquired knowledge and well-tested techniques, albeit with means much simpler and more limited than those available under the Roman Empire. This disadvantage affected both sizing and construction of all foundation types, including footings.

Just as the Romans had done before them, mediaeval builders also built their foundations with projections. But when they determined the sizes of the footings, both in plan and in cross-section, they did not take into account either the magnitude of the loads born or the nature of the load-bearing soil.

This carefree attitude regarding mechanical problems, combined with the construction of buildings of great height (towers, cathedrals) are the principal cause of the movements, cracks and collapses suffered by many of these buildings.

We may, however, highlight a building solution which is used with great frequency from the 11th century onwards, to form the solid base for foundations on soft ground in the presence of water. It consists of placing boards to form a grillage under the foundations, with the intention of reinforcing and levelling out the ground to become the plane of support.

It is no surprise that the use of these boardings should have become widespread, nor that it lasted until well into the 19th century, because amongst its several advantages, the following may be singled out:

— In muddy ground, the bottom of the footing could be made level simply and with ease.
— The timber grillage was comparable to the reinforcement of the foundation, the only kind available at that time, when steel was not yet in use in building construction.
— In comparison to piles, which as will soon be seen were the other typical solution for laying foundations on soft grounds in the presence of water, timber boardings required no special means for their setting and consumed much less in the way of materials.

The period spanning between the Renaissance and the first Industrial Revolution is notable mainly for the appearance of the first written rules for the sizing of foundations.

In theory, these rules take into account (or at least attempt to) the magnitude of the loads born and the nature of the load-bearing soil. But in practice, the inability to evaluate these parameters make such considerations simply declarations of intent.

The fact that the criteria proposed by the different authors of treatises should be so widely varied indicates the confusion reigning on such matters, although we could point out that in all treatises prior to the 18th century, authors agree on determining the size in plan of footings exclusively in relation to the width of the element they supported. (See figure 7).

In relation to these pre-18th century criteria it would seem convenient to list some facts gleaned on reading the texts. (See figure 7, again):

— With no apparent motive (although, no doubt, for economic reasons) the sizes of the foundations proposed by different authors become smaller and smaller.
— Since when sizing structural elements only their own dead load was taken into account, internal walls were mistakenly given less width than external façade walls. And the dimensions of the foundations carried the same error, depending as they did on the width of the element they supported.
— From the 17th century onwards, some authors of treatises (Bullet, Belidor), recommend that for external façade walls excentric foundations be built, with greater projections outwards than towards the interior of the building, basing this on the fact that «all external façade walls tend to lean outwards».

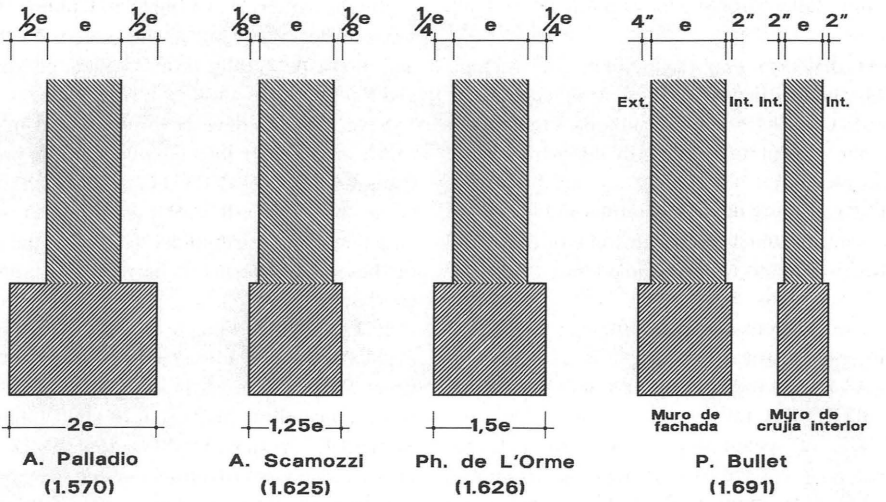


Figure 7
Sizing of foundations in treatises prior to the 18th century

This off-centre placement of the foundations for external façade walls is neither fanciful nor mistaken, since the make-up of old walls (with more or less noble, quality linings concealing heterogeneous infill, loose, very porous rubble or even earth) allowed neither the loads due to the structural elements holding the roof up nor those loads caused by the swelling of infill materials induced by water infiltration to be resisted. And these thrusts acted mainly on the outer face, the inner one being far more sheltered, drier, and, thanks to the bracing provided by the flooring, kept in a more stable position.

In relation to the depth of foundations, authors of treatises before the 18th century almost always state a fixed size, probably the one commonly used in their native homeland or region. However, these authors always recommend that if having excavated to this depth no *«firm ground»* had been found, digging should continue until it was.

In the latter years of the 17th century two new criteria for determining the size of footings appear, namely those due to Goldmann and Penther, which turn out to be the most successful of the whole period of time studied in this paper. It is a pity these treatises should have enjoyed such little dissemination, a fact probably due to the difficulty experienced by readers of latin descent when consulting the original German texts.

In these two criteria, the width of the footing does not depend on the width of the element supported, but rather on the depth of the foundation itself. And what is a complete novelty is that this depth is in turn determined in relation to the load-bearing characteristics of the ground.

In particular, Goldmann recommends the depth of the foundation be determined beforehand, by means of site investigation with dynamic penetrometers.

It would be convenient to note that Nicolaus Goldmann, an architectural theoretician who lived between 1611 and 1655, was the inventor of the first known dynamic penetrometer, whose construction, in the year 1699, signified the first great transformation of site investigation techniques for building purposes.

Indeed, until the construction of this first penetrometer, the characterization of the ground which was to support any given kind of building foundation was arrived at purely in relation to the physical and organoleptic properties of the uppermost layers of soil. On the other hand, from the early years of the 18th century onwards, when plenty of equipment was constructed (see the book *«Civil Engineering around 1700»*, by Jensen), the ground's resistance to penetration at depth became the essential information for evaluating its quality, at least in the case of important buildings erected near

water, or in it, belonging to what is today the field of Engineering.

However, in normal everyday building construction, and within the particular field of Architecture, the recommendations of 18th century authors of treatises in relation to the sizes of footings hardly differ from those of previous treatises.

Nevertheless, given their repercussion, two of the recommendations which appear in some of these 18th century treatises could well be quoted here:

— That in order to determine the size in plan of footings, not only the width of the element supported should be taken into account but also its height.
— That if on excavating a set depth (varying between 2 and 5 feet) no *«firm ground»* should be found, the excavation should be stopped and the foundations laid in good quality masonry.

The first of these two recommendations is quite reasonable, insofar as taking the height of the supported element into account represents, to a certain extent, the introduction of the magnitude of loads into the design process of footings.

But the second of these recommendations is not only completely unjustifiable but also totally mistaken, since the load-bearing properties of the ground disappear from the process of sizing the foundations altogether. And this at the onset of the first Industrial Revolution.

ANTECEDENTS OF DEEP FOUNDATIONS

As with shallow foundations above, we will begin with a brief critical analysis of the causes which led to the appearance of the prototypes of deep foundations before going on to study their chronological evolution.

Prototypes of shafts

There is no doubt that in all regions and cultures the excavation of pits is closely linked with mining and with the search for subterranean water. Proof of this is that shortly before the Neolithic period flint was already being sought using underground galleries, dug out with animal bones and entered by means of vertical shafts (Kérisel 1985).

But the earliest shafts linked to building foundations seem to be those built in the eastern Mediterranean, and more specifically in the regions of Mesopotamia and Egypt.

Several shafts have been discovered in the region of Mesopotamia which date back to the period going from 3000 B.C. to 2000 B.C., and which form part of some of the earthworks serving as supporting structures for the ziggurats. However, the excavation of these shafts seems to be related to some kind of esoteric ritual.

In Egypt, according to professor Rodríguez Ortiz (1989), the use of a limestone caisson for the foundations of tombs, towards the year 2000 B.C., is the most outstanding antecedent of shaft foundations. In particular, of those built below water using the characteristic and traditional system of the Egyptians: the *«zarbbiyeh»* also known as *«the mining caisson»*. (See figure 8).

In Babylon, the ruins of the Hanging Gardens, dating back to the year 600 B.C., may belong either to shaft foundations or to a structural system based on piers interconnected at their tops by arches or vaults, depending on whether when starting the foundations the builders dug shafts or removed earth wholesale. (See figure 9).

But whatever the building system used for these gardens, the use of their structural system for the construction of foundations could be very advantageous from the economical point of view. In

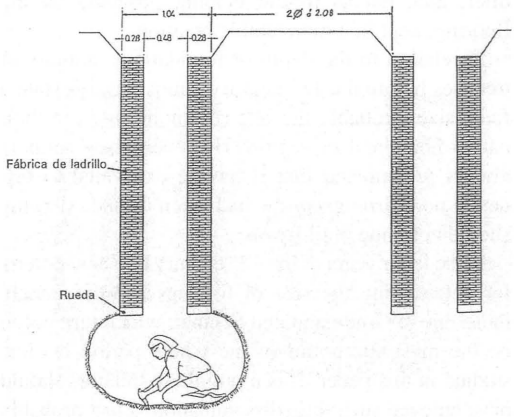


Figure 8
The *«zarbbiyeh»* or *«mining caisson»* (Kérisel 1985)

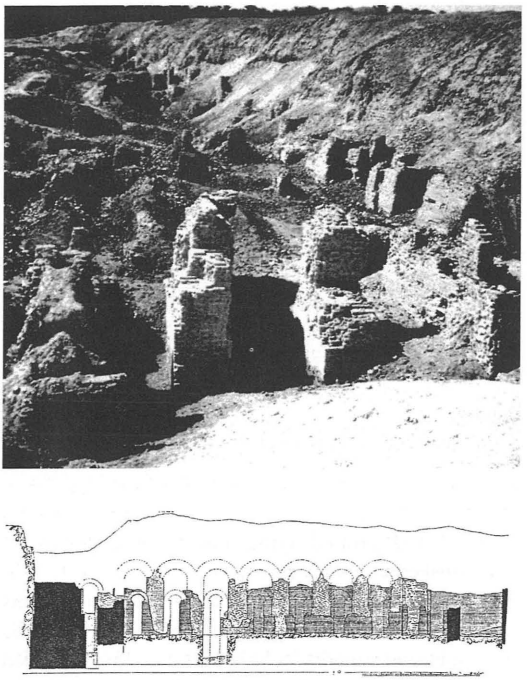


Figure 9
Foundations of the Hanging Gardens of Babylon (Giedion 1966)

fact, in those cases where the adequate strata were at a greater depth than expected it was far cheaper to build a set of shafts, at intervals to each other, and tied above by arches or vaults, than a strip foundation excavated to the same depth as these shafts.

Prototypes of piles

The antecedents and/or prototypes of piles are the log walls built in the primitive lakedwellings of the danubian region, belonging to the Neolithic period.

In the beginning (5000 to 4000 B.C.), these walls are completely independent of the flooring plinth, their logs driven into the ground to a depth of between 1 and 3 metres.

But, as has already been mentioned, the evolution of primitive plinths led to the appearance, towards 3000 B.C., of the first timber grillages built on piles. (See figure 4, again).

It seems that the location of these early lakedwellings was initially by the lakeside. But this building type also allowed a much more advantageous kind of settlement, from the defensive point of view: settlement within the lake itself. All that was needed for this was to lengthen the piles, but this entailed two new and important problems:

— Keeping the piles upright, even against the current or the waves.
— Finding tree trunks which were on the one hand long enough to be driven into the bed of the lake and on the other hand light enough to ensure penetration, given the scarce means then at hand.

The need to keep the piles in their proper position leads to the first solutions using bracing to reduce the free spans of the logs and to stabilize them, between 3000 B.C. and 2700 B.C. These solutions are already employed in some of the lakedwellings belonging to the third phase of settlement at the archaeological site in Le Weier. (See figure 10).

And the need to find long and lightweight tree trunks which would penetrate with greater ease leads, between 1800 and 1300 B.C., to the first solutions using composite piles, and the first treatments of the tips of the piles (carving and hardening by fire). As examples of composite piles we could cite those built at Fiavè, some of which reached 12 or even 13 metres in length, in two approximately equal sections.

All these solutions prove that towards 1300 B.C. there was a rather accurate knowledge of pile foundations, arising from the need to support certain structures (lakedwellings) on particularly soft and wet ground.

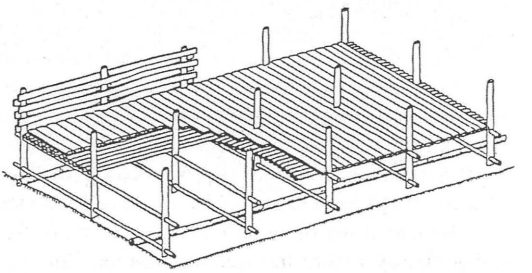


Figure 10
Bracing between piles in lakedwellings of the third phase of settlement at the Le Weier site (Pétrequin 1984)

Chronological evolution of deep foundations

Within the borders of the former European provinces of the Roman Empire, during the period of time studied in this paper, deep foundations were built using shafts or piles.

It should be noted that the word «deep» applied to these foundations is in fact relative, and only valid for their period of time, since until well into the 18th century the depths reached with this type of foundation rarely exceeded 3 or 4 metres.

It should also be noted that in the period studied and within the field of Architecture, the use of deep foundations is fairly rare and confined to a few cases, but not all, of building on poor ground.

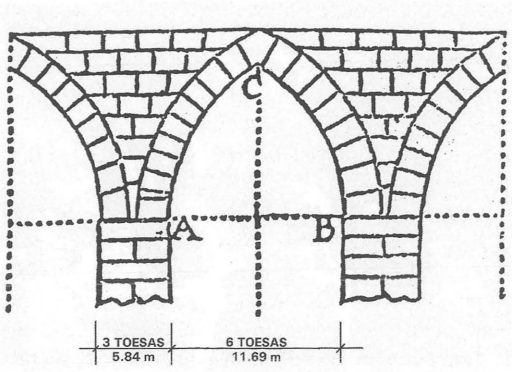


Figure 11
Sizing shaft foundations according to Bullet's treatise

Evolution of shafts

Within the borders of the former European provinces of the Roman Empire, it seems no true shaft foundations were built until well into the 19th century. Proof of this is found in the following:

- Examples of such foundations are scarce.
- Until the latter half of the 17th century, treatises contain no rule specific to this kind of foundation, no method of determining shaft dimensions or their configuration in plan.
- The fact that when at last these specific rules do appear it seems that the authors determine the dimensions of the shafts and their configuration with no other aid but experience in the cross-section of piers and the spans of arches and vaults forming part of superstructures previously built. (See figure 11).
- Until the 18th century, it does not seem to have been deemed necessary to take shafts down to firm ground. Moreover, almost all authors agree in considering tying shafts with inverted arches a way of avoiding differential movements between columns, movements which would have been almost negligible had those same columns been built over shafts resting on firm ground.
- Until the 18th century, techniques of site investigation for building purposes were very basic and their use did not allow prospecting depths beyond 2 or 3 metres, so that the quality of the ground lying under those levels of inspection was unknown.
- Until the 18th century, according to the contents of treatises, the characterization of ground as the plane of support for buildings was always carried out according to its physical and organoleptic properties, and not its mechanical properties.

Judging by the antecedents there is no doubt that this type of foundation was known at least since the Roman period, but in real constructional practice, shaft foundations were reduced to simple tied footings, albeit at a slightly greater depth than usual.

From the 18th century onwards, almost all authors of treatises recommend shafts *«built off a firm bottom»* for the foundations of buildings of a certain size on poor ground.

These recommendations appear closely linked to the phenomenon of urban growth, from which derived the need to build in formerly marginal areas, where, besides having to cope with grounds whose properties for building purposes were unknown, former rubbish dumps, tips and quarries for building materials were located.

However, it does not seem that true shaft foundations were built even during the 18th century. And this because almost all authors of treatises base their recommendations on one same example, which moreover is not in fact a shaft foundation at all, but simply a case of soil improvement by substitution: the church of Sainte Généviève, placed over a former

quarry, whose architect, M. Soufflot, ordered all the holes encountered during excavations for the footings initially intended to be filled with brickwork.

The 19th century is the age in which shaft foundations go beyond mere theory to become a fairly frequent type of foundation used in real building practice.

This was entirely logical, bearing in mind that use of this system is conditioned by the presence of great depths of poor ground, and until that time, when the steam engine was incorporated to prospecting equipment, the available techniques for site investigation, even with the most modern 18th century penetration equipment, could not reach depths of over 7 or 8 metres. And so it was not possible to ascertain the nature of ground at great depths.

However, although during the 19th century it was already possible to investigate ground at great depths, the inability to evaluate its parameters of resistance led to the sizing of shafts being carried out completely independent of the ground's properties, as if they were no more than pillars subject to simple compression.

According to this criterion, the indispensable condition for the proper mechanical functioning of this type of foundation was to take them deep enough to encounter very firm ground, of a rocky nature, which would offer at least the same resistance as the masonry with which the shafts were filled. And this seems to have been done in some of the singular buildings where this type of foundation was used. In fact, various authors agree in stating that for the church at Montmartre, shafts were excavated to more than 30 metres depth, in order to rest on a rock of gypsum.

Evolution of piles

Within the borders of the former European provinces of the Roman Empire, during the period of time studied in this paper, piles are employed mainly as a technique for soil improvement, not as a type of building foundation.

Moreover, one can safely say that from the Roman Empire until halfway through the 18th century, most of these foundations are really footings resting on a set of closely-packed stakes driven into the ground.

As has already been mentioned when dealing with shallow foundations, the Romans developed this technique in order to build on very soft ground, and its good results led to its use becoming widespread and lasting, with slight variations, over the centuries. The foundations of mediaeval buildings erected in the cities of Venice and Amsterdam bear witness to this.

In the city of Venice, a somewhat clumsy method was used which consisted in, for one same building, supporting the footings of the external façade walls facing the canals on stakes driven into the ground, but resting those of the internal walls directly on the ground. (See figure 12).

Some authors (Fleming 1985) declare the origin of this absurd building system was related to the existence of two different phases of construction: an early one which might be termed the urbanization of the city, in which before buildings were undertaken the ground was compacted by driving stakes into it, and a later, more gradual one during which buildings were erected.

But even if this had been the case, this supposed second stage, which must have spanned a rather long period of time, made the dismal results of the construction method employed evident. So much so, that Venetian builders learnt to use numerous ties in the superstructures of their buildings, in both timber and iron, in order to minimize the effects of ground settlement. (See figure 12, again). And yet these same builders failed to realize that they should change the system of building foundations used, no doubt due to their inability to evaluate any loads other than those directly derived from dead loads.

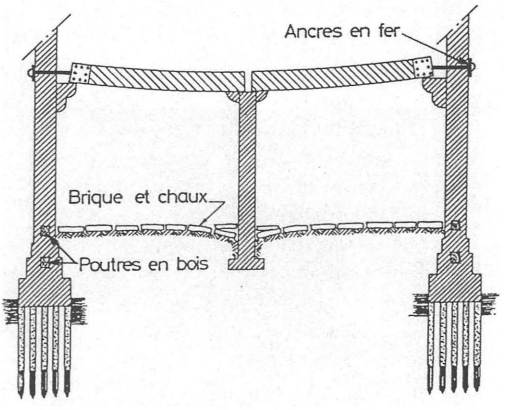


Figure 12
Traditional foundations of Venetian buildings (Kérisel 1985)

It should be remembered that Renaissance authors of treatises make the same mistake as Venetian builders when giving internal walls and footings widths far smaller than those of external façade walls. The only difference is that, in Venice, the façades were in direct contact with water, and so not only were their footings larger than internal ones, but they were supported on stakes driven into the ground. And this combination of poor ground conditions, erroneous sizing and the use of two different systems of building foundation for the same building simply worsen the effects of a kind of movement very typical of old buildings: the subsidence of their central section.

In the city of Amsterdam, a variant of the Roman solution was used which consisted in sawing the tops of the stakes off to a true horizontal plane, on which were then laid thick planks, far easier to build the foundations proper on. (See figure 13).

This solution, combining piles and timber grillage, spread to all areas of present-day Holland, and the remainder of the former European provinces of the Roman Empire, in which it must have been used quite frequently. As a matter of fact, the pile foundations proposed by all authors of treatises until well into the 18th century always combine piles and timber grillage, in three different variants, that are:

— Boarding resting directly on piles, as in Amsterdam.
— Boarding resting directly on the ground, with sheet piling surrounding the foundations, enclosing them and protecting them, in the presence of water, from subsidence.
— Boarding resting directly on the ground, combined with piles driven into it between the timber beams.

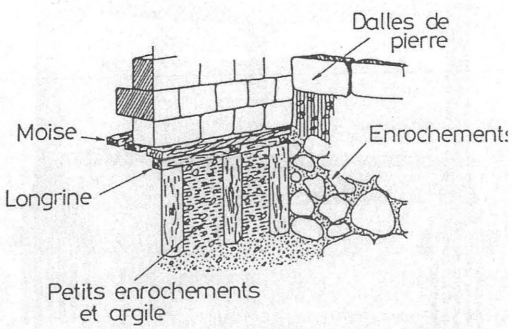


Figure 13
Foundations of a pier for a bridge across the Loire at Beaugency (Kérisel 1985)

But besides the building solutions recommended, the treatises also reveal considerable evolution in the criteria used for sizing and arranging piles in plan, offering ever more successful solutions over the whole of this period spanning from the 15th century to the dawn of the first Industrial Revolution.

With respect to sizing criteria, it should be pointed out that authors prior to the 18th century determine the diameter of piles in relation to their length, and their length in relation to the height of the element supported by them. Later authors also determine the diameter in relation to the length of the pile, but this length is now determined in relation to the quality of the ground.

As a result, in the theoretical field dealt with in the treatises, and coinciding with the turn of the 18th century, piles cease to be merely a technique of soil improvement and become a fully blown system of building foundation.

However, this change is delayed much further in real building practice, due to the fact that the length of piles was strongly limited and conditioned by the defficient machinery used for driving piles. So much so, that a length of only 5 m was already thought to be exceptional. And this situation lasted until the steam engine was incorporated into the equipment used, well into the 19th century.

With respect to the criteria used for the arrangement of piles in plan, it would seem that until Gautier's treatise, published in 1728, the interval between piles had always been determined according to the old rule of *«as much space empty as full»*, with which the separation obtained was obviously equal to a diameter. This was reasonable, bearing in mind that at the time, the main aim of using piles was to compact ground which was to support foundations.

However, Gautier proposes that the distance between piles be variable, depending on the depth to be reached and the load to be born. As a result it isn't strange that it should be this same author who provided what seems to be the first reference to the pile driving sequence, in which he states the order to be followed. (See figure 14).

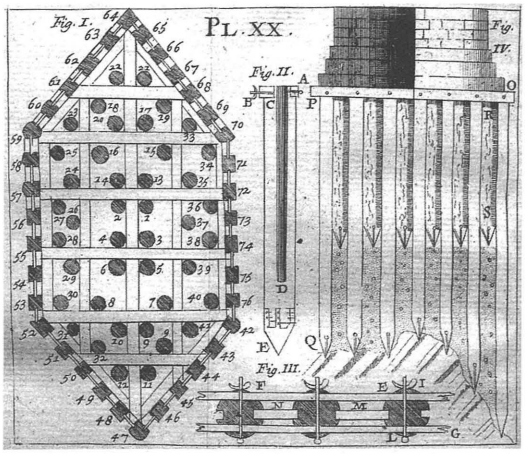


Figure 14
Pile driving sequence in a timber grillage foundation with infill piles (Gautier 1728)

It is not strange that Gautier's new criteria should modify what had until then been understood by driving to refusal. Since the Roman period, the need to arrive to refusal was maintained, but this was judged solely on account of the penetration achieved with each individual blow.

But halfway through the 18th century, Perronet already links refusal to the load-bearing capacity of the piles, and the method employed to drive them into the ground, possibly because it was at this time that the real transformation of pile-driving equipment took place.

Sure enough, although since the mid-15th century various attempts to invent pile drivers followed one another, such as those proposed by the authors Francesco di Giorgio (1450) and Juanelo Turriano (1595), the truth is that they had no immediate practical application in building construction, either because such machines were never built or because they were not adopted by their contemporaries.

As a matter of fact, until the beginning of the 18th century, when the first automatic mechanisms for releasing the drop hammer appeared, pile-driving used to be done manually, using very primitive hammers, whose origin would seem to pre-date even the Roman era. (See figure 15).

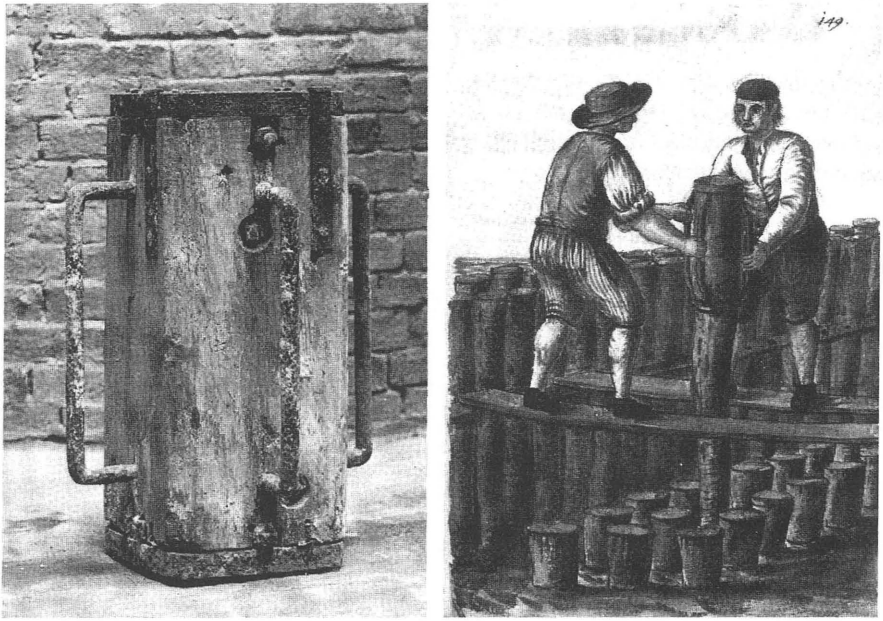


Figure 15
Manual drop hammer (Fontana 1980)

Conclusions

In the light of what has been said, and as a final conclusion to this brief summary, it can be stated that within the borders of the former European provinces of the Roman Empire, during the period of time spanning from the appearance of the first prototypes of foundations up to the dawn of the first Industrial Revolution, the evolution of both the techniques used for building foundations and the criteria governing their sizing and construction has been very slow, and limited mainly by the following factors:

- Inadequacy of the means available for site investigation.
- Ignorance of the ground's load-bearing properties and methods of evaluating them.
- Ignorance of the mechanical functioning of structures and the methods of evaluating any loads other than those derived directly from dead loads.
- Ignorance of mechanical soil-structure interaction.
- Iinadequacy of the means available to put into practice certain kinds of foundations (shafts and piles).

It can also be said, however, that in this same period did see an improvement in the building techniques used for foundations, linked mainly to the need to resolve problems arising from the construction of buildings of a certain importance on poor ground.

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The adventure of the Guastavino vaults

Javier García-Gutiérrez Mosteiro

This paper registers among the investigative works conducted for the «Guastavino Co. 1885–1962. The Re-invention of the Vault» exhibition, inaugurated at the *Museo de América* of Madrid in October, 2001 and later presented at the *Universidad Politécnica de Valencia* and the *Colegio Oficial de Arquitectos de Barcelona*. It was organized by the *Instituto Juan de Herrera* (ETSAM), the *Centro de Estudios Históricos de Obras Públicas y Urbanismo* (CEHOPU), the *Subdirección General de Arquitectura del Ministerio de Fomento* and the Avery Architectural and Fine Arts Library of the University of Columbia, and was overseen by the author with the collaboration of scientific coordinators Santiago Huerta and Salvador Tarragó, and researchers Esther Redondo and Gema López Manzanares. The research is registered in the exhibit book-catalogue *Las bóvedas de Guastavino en América* (2001. Madrid: Instituto Juan de Herrera).

In the history of construction, several episodes characterized by the transfer of vaulted forms from Spain to America could be related.[1] Among these is one of special significance: that featuring Guastavino, who arrived at the port of Manhattan from Barcelona in 1881, ready to found a construction practice in the Unites States with roots in the Mediterranean vernacular tradition. Decades later, the system he developed —now known as the Guastavino System— had been used to erect more than one thousand important vaulted constructions in North America, several hundred of them in New York, and had characterized a good portion of the most important buildings in the United States: from the cathedrals of the medieval revival to the huge, modern vestibules of skyscrapers . . .

This well-defined chapter in the history of construction is concerned with outlining Guastavino's true contribution to the historical experience of the timbrel vault; demarcating the work undertaken by Rafael Guastavino Moreno and that conducted by his son, Rafael Guastavino Expósito; questioning their professional mandate —architects, businessmen, propagandists or inventors?—; analysing the terms of the professional relationships they maintained with their American architectural collaborators; and, finally, discussing the reasons for their sudden success and, also, their subsequent disappearance.

The architectural quality of the spaces created by the Guastavinos is not elusive. Its effect could, perhaps —among the frequent *slanted* constructions of the time— be best described by the order and dignity his constructive reason granted to architecture. It is surprising, therefore, to learn in what scant measure concrete references to the Guastavinos appear in publications which dealt profusely with the constructions they erected: their name has remained overshadowed, so many times, by those of the great architects with whom they collaborated.

George R. Collins, the great and studious —shall we say— *reivindicator* of the Guastavinos showed just how strange it is that so little attention is paid to

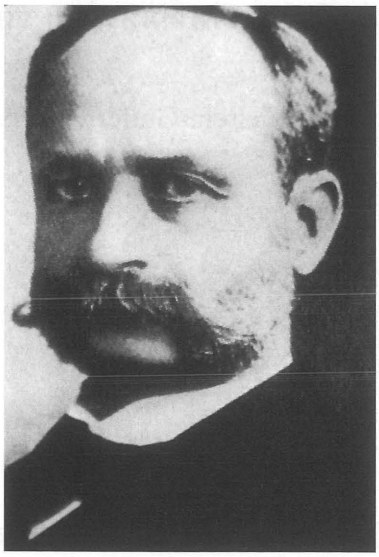


Figure 1
Rafael Guastavino Moreno (ca. 1880)

this singular chapter in the history of vaulted construction. Often times, it was precisely the distinction of containing a *Guastavino vault* as the principle —if not the only— spacial effect which allowed many of the buildings constructed between the 1880s and the middle of the twentieth century to be included in the most selective classifications of United States architecture (Collins 1968, 176).[2]

The Catalan pacing

Rafael Guastavino Moreno (1842–1908) was born in Valencia and studied at the *Escuela de Maestros de Obras* of Barcelona (1861–1866) (Bassegoda 1973, 86),[3] where he had such important professors as Juan Torras and Elías Rogent;[4] they pointed him toward the system —then still in an embryonic state— he would later develop (Guastavino 1892, 9).

In 1868, he presented as part of his design for the Batlló textile factory in Barcelona what would constitute a veritable technical revolution, and for which his name would receive temporary distinction in the world of Catalan construction. The spectacular loom room, covered by a series of spherical vaults rested upon metallic supports, was the first great prototype of the incorporation of what Guastavino called «cohesive construction» in the configuration of a new kind of industrial architecture.

The rapid growth of industry in Catalonia in the second half of the nineteenth century required a system of construction for large manufacturing buildings that could effectively combine economic considerations and fire safety measures. Guastavino's success consisted in returning to a technique long-employed in popular Catalan architecture, that of timbrel vaults,[5] and, through the incorporation of current materials —fundamentally portland cement in place of lime mortars— converting it into a modern system of construction and further developing it with modern perspectives.

The landmark Batlló factory prompted many businessmen to take an interest in the process, securing Guastavino other important projects; it also served to change the opinions of construction professionals with respect to the modern application of this type of vault.[6]

From here, Guastavino managed to extend this system of construction and formulate new proposals for large urban developments. This was the setting for the «Improving the Healthfulness of Industrial Towns» study which he presented at the Philadelphia Foundation Centennial Exposition (1876). Here, he presented the advantages of his system of construction, characterized by its resistance to fire, and applied them to the search for urban healthfulness and rapid industrial growth.[7] The fact that his report was favourably received in the contest, gaining distinction with a prize, awakened in Guastavino a certain intuition that this success in his first contact with the United States would lead to others. He understood that North American society, in the middle of a human and material resources boom, offered him unforeseen opportunities. What to do —even considering his life's other circumstances—[8] but to set off for the United States five years later at the risk of losing the prestigious professional position he had earned in Catalonia?

Encountering New York

When Guastavino arrived in New York in 1881, he was met with a panorama that included two factors

which would influence his trajectory: on the one hand, an openness to the new building materials —portland cement, laminated steel, concrete— which were replacing traditional and combustible wooden structures; on the other hand, and as a counterpoint to what the Chicago School was putting out in those years, the progressive expansion of a taste for *Beaux-Arts*, whose general acceptance across the whole of the country would come about later.[9] Also, and of more than trivial importance, the deep mark left by the Chicago fire ten years earlier was still being felt.

Guastavino's precarious arrival in the United States did not allow him, initially, to carry out the type of work he had been doing in Spain. Yet, by 1883 he had won the competition for the Progress Club building in New York and constructed several residential buildings, in which he *programmatically* employed timbrel vaults as a fire-resistant construction system.

From these same beginnings in New York, he practised an active policy of patenting fire-resistant building procedures based on bricks and vaults *a la catalana*. By 1885 he had registered the name «Construction of Fireproof Buildings» and, after a very few years, with a conglomeration of patents grouped together below the denomination «fireproof», he was able to produce materials (special brick pieces, mortars, metal reinforcers) and building procedures (large timbrel vaults, forged vaults, staircases *a la catalana*, partitions . . .) which conferred an operative efficiency upon the soon-to-be-called *Guastavino System*. Guastavino's great intuition was reinvigorated by the possibilities that were opening up to him; he was following a path very distinct from that of the strict exercise of professional architecture.

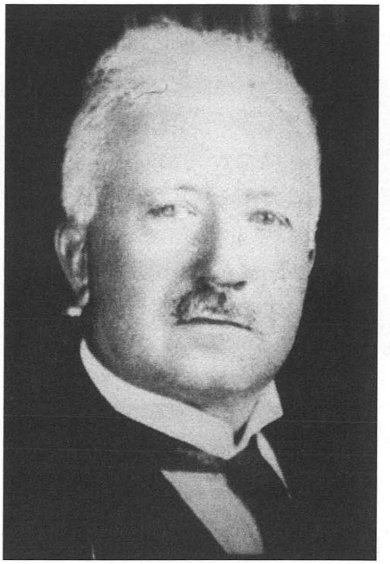


Figure 2
Rafael Guastavino Expósito (ca. 1925)

The *Guastavino Fireproof Construction Company*

With his first great work, the Boston Public Library (1889), he had the opportunity to put the advantages of his system of vaults to the test against other customary processes, and to lay bear —with his boldly dressed intradoses— some new and attractive formal possibilities (in other respects quite in keeping with the aesthetic trends of the moment). As a result of this project, conducted in collaboration with the prestigious architectural firm McKim, Mead and White, he received wide-spread resonance and publicity, decisive in defining his professional orientation.[10]

With the confirmed acceptance of his system of construction, and counting on the security afforded him by his registered patents, he founded the Guastavino Fireproof Construction Company in 1889. From this moment on, his work —with the option for independent architectural activity definitively rejected— is tied to the company, such that when we refer to *Guastavino vaults* we are referring to a complex production process, thoroughly developed at the time, which long-outlived its founder: after his death it would be his son —Rafael Guastavino Expósito (1873–1950)— who would take charge of the business, which would not go into liquidation until the year 1962.[11] After the firm's liquidation, professor Collins aquired the vast Guastavino Company archive for the University of Columbia, where they are currently held.

The skill with which Guastavino founded his business is evidenced by the fact that, only ten years after his arrival in the United States, he had opened offices in several cities —New York, Boston and



Figure 3
Fire-resistence test with a timbrel vault (New York, 1897). (Guastavino is the second from the left)

Chicago— and had amassed a large number of important constructions.[12] What resources granted Guastavino such an early and resonant success, having started from nothing? One consideration which, in large part, answers this question is the progressive control that the company was establishing in all phases of the construction process: designs and patents, testing, fabrication and manufacture of distinct types of brick, distribution and execution. This control brought with it a high amount of quality control, an active collaboration with project architects, an increase in working speed and a decrease in the price of construction.

The work undertaken by the Guastavino Co. over seventy years, far from being restricted to the chores of labour contracting and patent control, must be judged as essentially *architectural*, definitive in the spacial and formal lineage of buildings. The conformation of the architectural space that necessarily accompanies the vaulted system makes it impossible, in many cases, to treat form separately from construction; this lends particular interest to the study of the relationship between the company and the teams of architects with which they collaborated (Parks 1999, 23).

The Guastavino system offered a copious fountain of formal and spacial resources, it made possible a creative relationship —receptive to experimentation and the search for different technical and expressive possibilities— with the personality of each architect. If with firms like McKim, Mead and White[13] he would explore, during many years of collaboration, extremely dissimilar spacial and structural organizations, with project authors such as Henry Hornbostel he would achieve maximum levels of innovation in the development and articulation of superficies,[14] and with teams such as Cram, Goodhue and Ferguson, particularly interested in the conditions of vault linings, he would demonstrate the modelling and acoustic abilities of the different materials the system offered.

If the architectural aesthetic which reigned in New York upon Guastavino's arrival favoured the success of his vaulted forms, linked in greater or lesser measure to previous languages, it is not less certain that the Guastavino system was able to abide by the new formal tendencies and, in many cases —embracing very dissimilar architectural types— it propitiated a modern language expressively inspired by constructive sincerity. Guastavino's work features, in any case, a discourse on construction: it is not at all strange that —

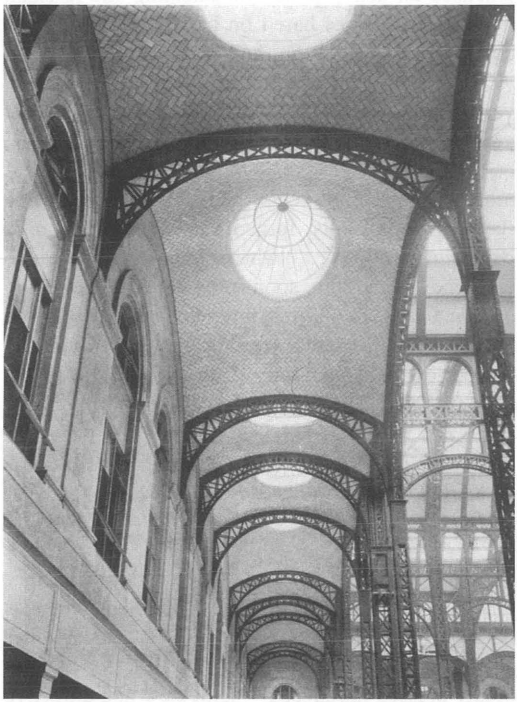


Figure 4
Pennsylvania Station, New York, 1905–1909. (Demolished in 1963). (With McKim, Mead &White)

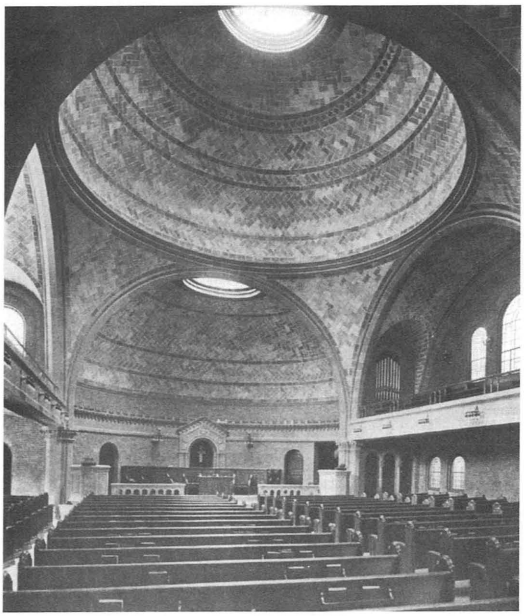


Figure 5
Amity Baptist Church, New York, 1907–1908. (With Rossiter &Wright)

as he affirms in his *Prolegomenos* (Guastavino 1896)—he held the deterministic constructive logic of his strict contemporary, Choisy, in such high esteem.

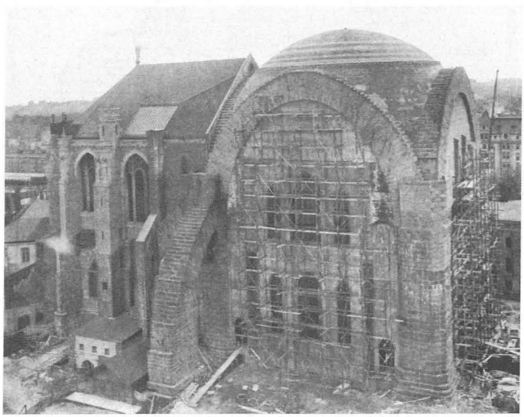


Figure 6
Construction of the Cathedral of St. John the Divine, New York, 1892–1932. (With Heins & LaFarge, Cram & Ferguson)

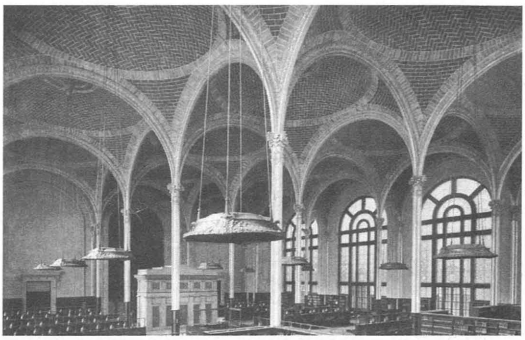


Figure 7
New York State Education Building library, Albany, NY, 1908.1911. (With Palmer & Hornbostel)

Utopia and Construction

As a counterpoint to the efficient diffusion of publicity with which the company always took great care, there is another aspect which stands out: the rigorous scientific and technical diffusion, by way of publications and reports to congresses, that Rafael Guastavino's system became. Even during his Catalan period, the treatises of modern timbrel vaults was decidedly non-existent; this motivated him, after his first successes in the United States, to publish several studies which led to the publication of his *Essay on the Theory and History of Cohesive Construction* (1892).[15]

This work, the most complete compendium of his ideas about construction, is a living defence of the

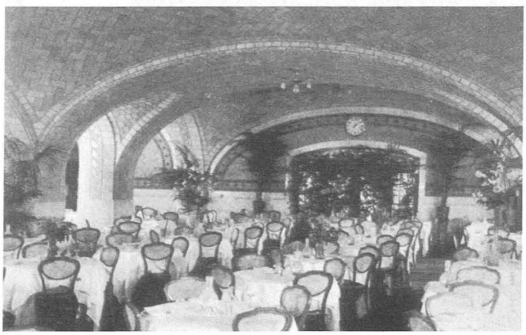


Figure 8
Vaults at the Oyster Bar, Grand Central Station, New York, 1911–1913. (With Reed & Stern, Warren & Wetmore)

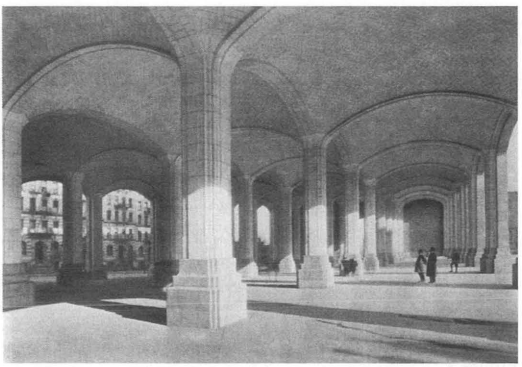


Figure 9
Queensborough bridge, New York, 1917. (With Palmer & Hornbostel)

timbrel vault system, in which he takes great effort to show its advantages over concrete construction (which he himself had explored in its beginnings) (Guastavino 1892, 14) and over traditional voussoir vaults. In this book —and in later publications— he also touches on what we could call a *philosophical* defence of the role that masonry has played in the history of construction. In contrast to the traditional gravitational system of vaulting, whose mechanism relies on the voissoir form (it would be possible, from a conceptual point of view, to join them without any adhesive), he presents the *cohesive* or *organic* system, in which the adhesive capacity of the mortar makes possible new and more economic processes, with a notable reduction, if not the elimination, of scaffolding systems. He understood, and defended, this system as being specially suited to the construction of his time; he affirmed, not without a certain utopian vision, that —with the progress of new mortars and their capacity for rapid setting—

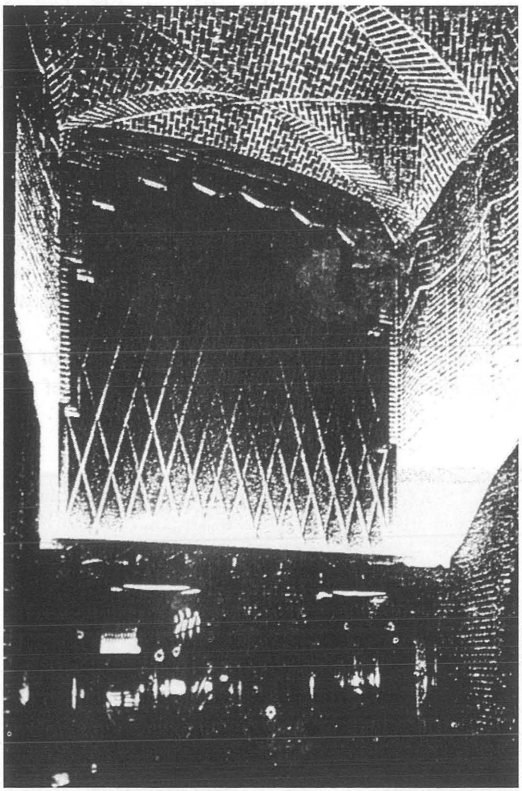


Figure 10
Lobby at the Western Union Building skyscraper, New York, 1929. (With Vorhees, Gmelin & Walker)



Figure 11
Advertising poster for the Guastavino Company, with several of the most relevant vaults built

cohesive brick masonry would be the material of the future (Guastavino 1904, 30).

Guastavino, whose name remains inextricably tied to the practice of timbrel vaults, advanced a new chapter in the long history of the construction of light or free-standing vaults. His constructive instinct discovered a way of understanding vaulted spaces, never-before seen in the United States; his *invention* would advance far beyond what had been known in Spain and —as a reflux— would arrive back here also, in the autocratic years following the Civil War, with remarkable consequences.

Rafael Guastavino surprises us, as do his almost utopian theories, with the prodigiously regal production of his admirable ceramic vaults, an eloquent illustration of his conviction.

Notes

1. The first was the encounter between both cultures itself: Pre-Columbian America was not familiar with this type of construction —a true *invention*— based on arches and vaults; . . . but soon the New World erected remarkable domes which would have —on their return trip— a profound influence in Spanish architecture. By the middle of the twentieth century, the ingenious constructor, Madrid architect Félix Candela, would fill Mexico with elegant, slender and surprising membrane-vaults, true «reinforced concrete trickery».
2. George Rosenborough Collins (1917–1993), professor of Art History and Archeology at the University of Columbia, was a studious enthusiast of Spanish architecture. His interest stems from his discovery of Arturo Soria; later he focussed on Catalan architects from the late 19th century, particularly on Gaudí, whose fame spread internationally during the 1970s, and he created the most important existing archive of modernist Catalan architecture (donated to the Art Institute of Chicago); his work led him to discover timbrel vaults, and from here to follow the work of the Guastavinos in the United States.
3. The schools of *Maestros de Obras* were shut down in 1869 (the new School of Architecture of Barcelona didn't begin to grant titles until 1875); the collective of the *Maestros de Obras* had, until that moment, an important role in Barcelona.
4. Rogent would come to be the first director of the School of Architecture of Barcelona.
5. Light vaults made with brick placed sideways, generally in several layers, that can be made with light or even witout scaffolding systems.
6. This process had come about by combining empirical experience and constructive instinct: little to none of the process or its methods of calculation had been systematized.
7. Guastavino released this paper when North American public opinion —still impressed by the fire that had nearly flattened the city of Chicago in 1871— showed a special sensitivity to security conditions in cities which, after the War of Succession, had been experiencing enormous growth.
8. He left for the United States —with his nine year old son Rafael— after his marital breakdown.
9. The Universal Columbian Exposition of Chicago (1893), in which Guastavino participated, was the event that did away with the advanced formal lines that had been deposited in the city over the years.
10. The technical publications of the time described their surprise at this process that permitted the raising of vaults without using scaffolding. Following the success of this work, in 1889 Guastavino was invited to give several conferences at the Massachusetts Institute of Technology's Society of Arts (these would later be collected in his *Essay* . . .).
11. In 1943, Guastavino the younger sold his stocks, leaving A.M. Bartlett as president. William E. Blodgett and, later, his son Malcolm, were decisive figures in the constitution and rapid development of the company: they directed the financial aspects of the business, and knew how to deal with the deep periods of economic depression that were appearing around the country; the Blodgetts were two fundamental pillars for the Guastavino Company, whose history remains thus described by the succession of two generations of surnames.

    The company's decadence would run parallel to the increase in the cost of labor and to the perfection and development of reinforced concrete technique, which allowed for already competitive vaults to be designed with thin membranes.
12. Even though the Guastavino Company's work reached nearly all the states in the country, it was principally centered around the East Coast.
13. With this celebrated firm, the Guastavino Company made, in addition to the aforementioned Boston Library, nearly fourty buildings over thirty years; among them: the University of Virginia en Charlottesville complex (around 1897) and the U.S. Army War College of Washington (1905); as well as many of the most important vaulted constructions in New York, such as the now disappeared Pennsylvania Railroad Station (1909) and the unusual syntax of glass ceramic vaults in the Municipal Building (1917).
14. Good examples are the Williamsburg and Queensborough bridges in New York (1903 and 1909)

and the *labroustian* library in the Albany State Education Building (1911).

15. This publication would be followed by others. In 1893, upon the occasion of the Congress of Architects at the Universal Exposition of Chicago, he presented «The Cohesive Construction. Its Past, its Present; its Future?», then published in *American Architect and Building News*. Later, in 1904, upon the occasion of the International Congress of Architects of Madrid, he presented «The Function of Masonry in Modern Architectural Structures».

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«Smooth, hard, clean, perfect» Terranova, history of a modern plaster

Emilia Garda

TERRANOVA: PLASTER AND POETICS

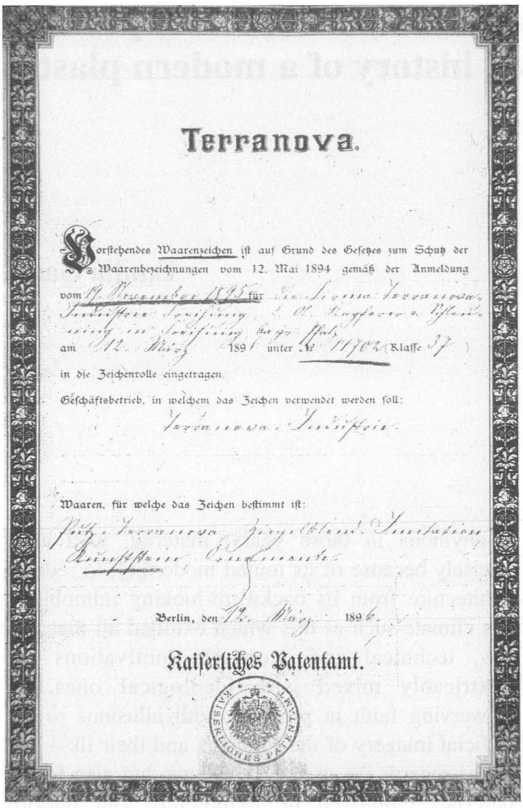
Developed in Freihung, Bavaria by Kapferer in 1893, «Terranova» —a ready-mix, factory tinted plaster for exterior facade use— came into widespread use in Italy starting in 1932, thanks to the efforts of Aristide Sironi and his plant in Via Stephenson, Milano.[1]

It was in this period that Terranova plaster first begins to receive extensive attention in technical journals, manuals, handbooks and advertising brochures; it figures in the statements and theoretical writings of the Rationalist architects; above all, it emerges as the finish material of choice —virtually to the exclusion of all others— for the facades of civil and industrial buildings, where it is applied in broad areas or more limited bands, used for contrast in loggias and arcades, with its myriad colors, now luminous and bright, now somber, lusterless and restrained, setting off other facade materials such as marble, natural or artificial stone, high-fired tile or glass brick.

For this material, created in reality over forty years earlier in Germany, Aristide Sironi shrewdly retained the original name (which was also maintained after the manufacturer's recent acquisition by Weber & Broutin, though in this case the motives were entirely different: to underscore —by using the same name as well as by other means— a sense of a continuing tradition). For Sironi, the intention was to promote the product as a new, innovative, modern and —why not? rational and economical (the two terms were almost synonymous in those years) material, well able, precisely because of its touted modernity, to redeem architecture from its backward-looking immobility. In a climate such as this which extolled all that was new, technical and economic motivations are inextricably mixed with ideological ones, an unswerving faith in progress with allusions to the artificial imagery of the Futurists and their ilk— not just as regards the use of Terranova, but also for all materials employed in architecture and interior decoration. So pervasive was this ethos that, frequently, synthetic materials —developed as substitutes for other, more costly products— ended by being more highly prized than the originals themselves. Such, indeed, was the case of the Bakelite used in place of amber or tortoiseshell, the Linoleum used to imitate briar or Persian carpets, and the plasters that were carefully contrived and treated to imitate stone.

The various defenders of the faith lost no time in pumping up the myth of the new materials, and the improbable virtues often attributed to them, so much so that a number of designers, including Figini and Pollini, felt the need to defend themselves from what they called «Another rhetoric, the most recent, the rhetoric of new materials» (Figini, Pollini 1932, 2–3).

Alongside the modernistic ideology, another theme that was widely viewed as essential in those years, deeply felt and vigorously promulgated, and which is closely linked to the use of new materials and the Rationalists' categorizing efforts, is the theme of



Terranova.

Vorstehendes Waarenzeichen ist auf Grund des Gesetzes zum Schutz der Waarenbezeichnungen vom 12. Mai 1894 gemäß der Anmeldung vom 19. November 1895 für Terranova Industrie Freihung, Kapferer & Co. Kapferer & Uhlich, Freihung in Oberpfalz, Bayern

am 12. März 1896 unter No. 14702 Klasse 37

in die Zeichenrolle eingetragen.

Geschäftsbetrieb, in welchem das Zeichen verwendet werden soll:

Terranova-Industrie.

Waaren, für welche das Zeichen bestimmt ist:

Putz, Terranova, Imitat. Quader, Imitation, Kunststeine, Ornamente.

Berlin, den 12. März 1896.

Kaiserliches Patentamt.

Figure 1
Patent certificate of 1896, conserved at the Weber & Broutin offices in Vienna and reading. *«This trade name was entered on March 12, 1896 as No. 14702 (Class 37) in the registry of trademarks on the basis of the law of May 12, 1894 governing trademark protection following an application filed on November 19, 1895 by Terranova Industrie Freihung, Messrs. Kapferer . . . and . . . Sectors in which the trade name «TERRANOVA INDUSTRIE» will be used: Terranova plaster, imitation facing brick, imitation stone, ornamental surfaces. Berlin, March 12, 1896 Imperial Patent Office».* (Weber & Broutin archives)



Figure 2
Terranova Pavilion at the 1932 Milano Triennial. (Weber & Broutin archives)



Figure 3
Visit by the King of Italy to the Terranova pavilion during the 1932 Milano Triennial. (Weber & Broutin archives)

ambient hygiene. At the typological level, the desire for hygiene —seen as the road to healthfulness— was responsible for sweeping renovations: horizontal windows, flat roofs that could be used as gymnasiums or gardens, etc.. When selecting materials, it led to a preference for those that were smooth and washable, would not harbor bacteria, and were free from cracks and joints. While the favored materials for exteriors were marble, granite or their more economical relatives, the «smooth, hard, strong, clean, perfect» plasters, as Gaetano Minnucci defined the various types of Terranova (Minnucci 1930), preferences for interior finishes ran to washable materials such as Lincruster; above all, however, it was glass (in ever-

more sophisticated forms such as Saint Gobain glass bricks, Opaline glass, Desagnat flexible glass, Civer tiles) which was preferred for its characteristic transparency and ability to reflect light.[2]

For building exteriors in particular, hygiene changed from being a functional requirement to an aesthetic concern, a guarantee of the smooth, perfect and incorruptible surfaces that were necessary to an architecture that relied heavily on simple geometrical elements. Particularly interesting in this connection are the opinions of two protagonists of the architectural experimentation of those years: Alberto Sartoris and Domenico Morelli.

Alberto Sartoris goes so far as to say that the simplification of architectural form is not a compositional issue but is rigorously functional in nature, as self-cleaning forms are an answer to the problem of materials that rapidly become obsolete:

> We have arrived at this type of simplification after a close scrutiny of public monuments. Observing the nudes found in all of Italy's squares, they will be seen to be blackened under the arms, between the legs, anywhere, in short, where rainwater does not pass. Under the nose, for instance, even if the personage represented is not moustached, the statue will have a pair of black whiskers, because dust builds up under the projections and the surface will look clean only where water flows over it. Trivial as they may seem, such considerations are extremely important in architecture. (Sartoris 1989).

Domenico Morelli, on the other hand, sees the use of new materials whose value has not yet been proved by experience (he is speaking specifically of the «new plasters» Pietranova, Terranova, Silexore, etc.,), together with the extreme simplification of forms and volumes, as perhaps the most critical aspect of Rationalist experimentation:

> I believe that one of the causes of the decay of Rationalist architecture lies precisely in the fact that the materials have not held up to the architects' intentions. The architecture that preceded this period (the Twenties

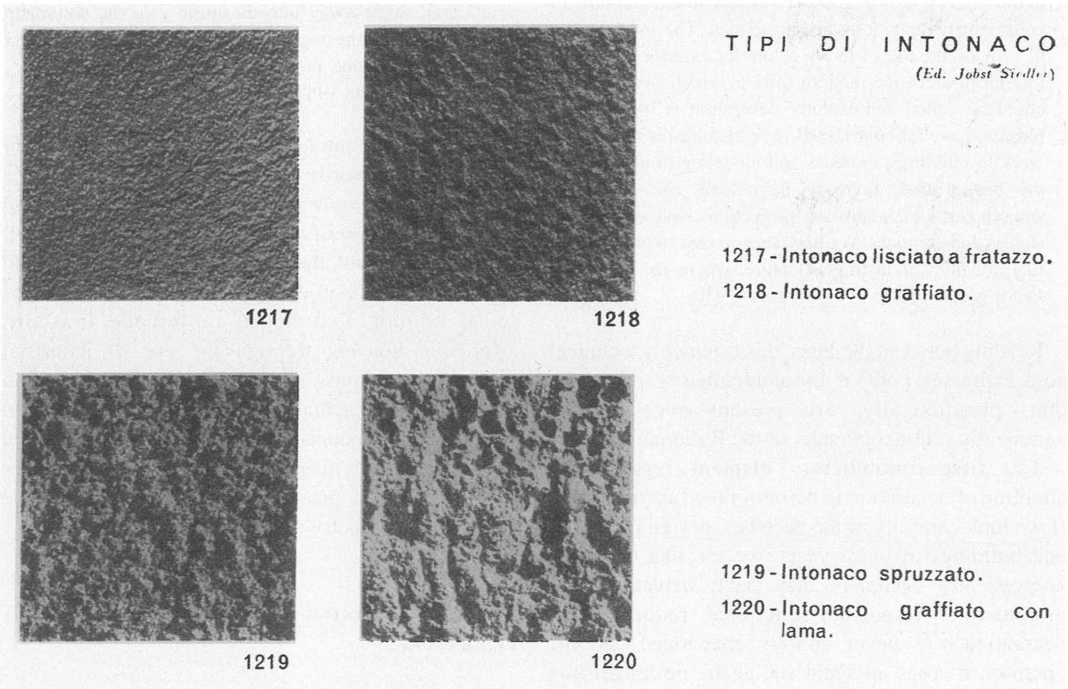


Figure 4
Examples of surface treatments: float-smoothed plaster, textured plaster, sprayed plaster, sgraffito. Griffini, Enrico Agostino. 1934. *La costruzione razionale della casa*, Milano: Hoepli, 437–438.

and Thirties) was based on decorations such as carved foliage and moldings, and was enriched with statues, frescoes and so forth. As the years go by, these decorations become dirty, obsolete, but they nevertheless retain a character of their own, something that time cannot take away . . . By contrast, modern architecture is based on clean, precise surfaces whose only ornamentation is the rhythm established by the window openings . . . Sadly, this type of architecture, even if finished with special plasters, plasters that are a bit out of the ordinary, solider than before, has not stood the test of time and has betrayed the expectations of its designers (Morelli 1989).

As Gaetano Minnucci wrote in *Architettura ed arti decorative* in 1930:

Trends in plasters have taken two directions, one concentrating on the plaster's surface form: while in past years especially, we have seen a true flowering of textures, with surfaces streaked, scraped, hammered, combed, and in short, roughened in every imaginable way, today's preference is for the smooth, hard surface. The other trend, which is some senses closely connected to the first, regards the plaster's composition, and how to color it in various long-lasting shades. The introduction of cement, the use of lively colors for exterior as well as interior plasters, the modern spirit to which anything that could be called architectural decoration is increasingly foreign, have all contributed to relegating the plasterer's work in moldings, cornices and modeling of all kinds to the background, favoring large-scale use of broad, smooth surfaces, where any projections have elementary shapes and contours. We have thus passed to productions that are more industrial in nature, where the economic factor predominates . . . (Minnucci 1930).

Reading between the lines, this ostensibly technical note expresses both of the contradictory principles that, paradoxically, are present even in the «eminently rational pursuits of the Rationalists».

The first contradictory element regards the abolition of decoration in favor of pure functionalism. If we look carefully at the sketches, design proposals and buildings of those years, we see that, however energetically designers may have striven for an architecture based on functional requirements, decoration was never entirely abandoned. On the contrary, it crops up again and again: no longer as a mere adjunct or overlay, but as a synchronic and consubstantial part of design. In other words, it was the material itself that was called upon to perform decorative functions, almost as an attempt to counterbalance formal simplification.

It is chiefly in finish materials, whether they be noble marbles and mirror-bright crystal, or humbler materials such as Terranova plasters, Buxus, Lincruster or Linoleum that we can descry, often under the banner of hygiene, a decorative intent. Frequently, this intent is pursued through a reliance on the chromatic qualities of natural materials and the intense, pure colors of artificial materials.[3]

The Rationalist architects, in fact, made extensive use of color. We must not be deceived by the black and white photographs we find in the magazines and journals of the time, and the washed-out, anemic image they give us: «the Rationalist house is cheerful, luminous, colorful» (De Guttry, Maino 1988). These colors are generally pure tones combined in graded or contrasting shades, as masterfully described by Giacomo Polin:

. . . at the beginning, colors have the names of things: yellow is lemon, red is coral, white is ice or ivory. Later, these colors, lively because natural, rational as are lemons or coral, shade away into the infinity of the chromatic spectrum, like the malachite green that the numberless veins of the stone prevent us ever from reaching . . . (Polin, Selvafolta 1982).

The second contradictory element emerges from the concluding words of Gaetano Minnucci, when he speaks of *« . . . more industrial in nature, where the economic factor predominates . . . »* (Minnucci 1930). If, on the one hand, the Rationalist period favored the humbler materials in deference to an ideological and social outlook that hoped to provide low-cost, affordable housing through the use of industrial processes and mass production, the buildings and rooms that were actually created were commissioned by the highly educated and progressive moneyed classes. Thus, the materials that were born humble as part of a social program often ended up, despite everything, as luxury materials.

Terranova plaster and the technical literature

As we have seen, Terranova plaster was not a new material, though this is how it was presented. Even in the technical publications that were designed to provide

information about the product, the accent is on its innovative character. Terranova, in fact, is numbered among the «new lightweight plasters» or —adding its presumed exceptionality to its modernity—among the «special plasters».

The properties that were required for these products, in fact, were light weight (indispensable for plasters that were applied thickly or were used to cover thin, light cladding materials), together with high mechanical strength (due to the product's high cohesion), good thermal and acoustic insulation (guaranteed by its cellular structure and comparatively low density), impermeability, resistance to freezing and weathering (high cohesion increases compactness, thus improving impermeability, while the presence of mineral fibers which «reinforce» the plaster eliminates crumbling and makes it less prone to ice damage), and, finally, good pigment absorption (unlike ordinary plasters, in fact, the new products are impregnated with color down to a certain depth).

Frequently, claims are also made regarding the product's «petrifying power» (or in other words, its ability to become rock-hard after a certain period, making it able to withstand extreme temperatures, impact and mechanical damage), which allegedly guarantees the smooth, perfectly incorruptible surfaces necessary to an architecture that achieved its effects through the use of simple geometrical elements. Very often, in fact, the new plasters, « . . . smooth, hard, clean, perfect», are used as «substitute» materials on facades, «in place of» the less modern and economical marbles and granites (Minnuci 1930).

In addition to Terranova, mention should also be made of other types of special plaster, named according to the factories that produced them: Jurasit, Pietranova, Silitinto, Stalfit, Terrasit, etc . . .

The cements used for this type of plaster included

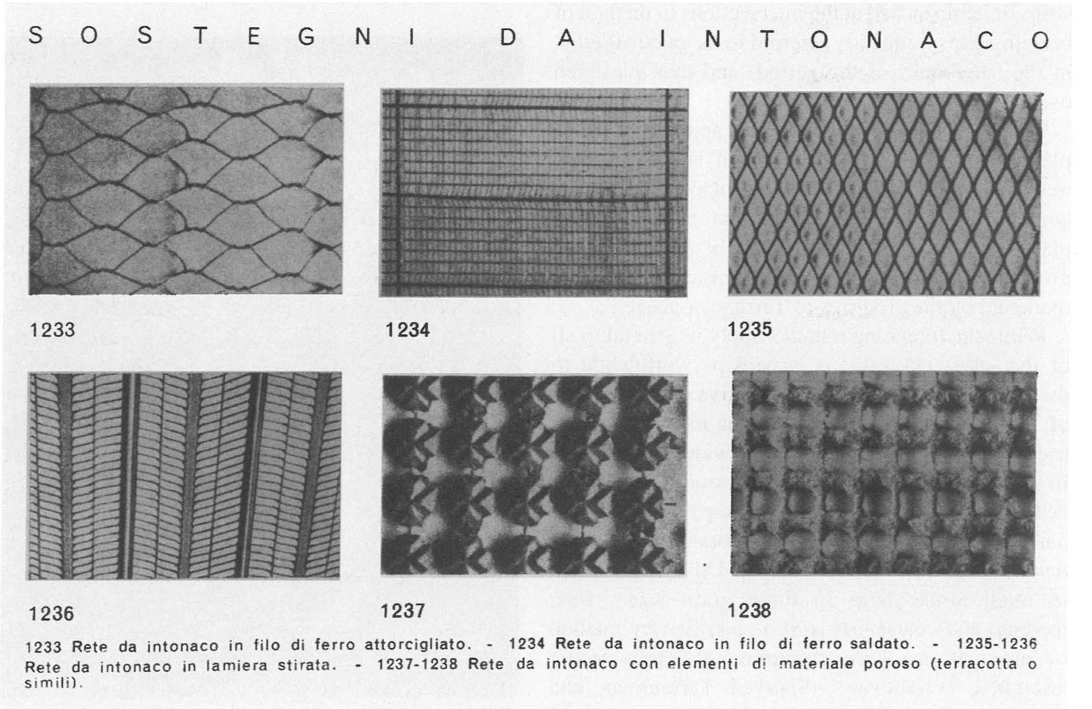


Figure 5
Examples of lathing. Twisted wire lath, welded wire lath, expanded metal lath, metal lath with porous elements (terracotta or the like). . Griffini, Enrico Agostino. 1934. *La costruzione razionale della casa*, Milano: Hoepli, 439

Duralbo cement (an extremely white, fast curing high-strength artificial portland cement produced in rotary kilns by Società Istriana dei Cementi at the latter's Pola plant), and Cromocemento (a tinted high-strength Portland cement produced by Soc. An. Cromocementi of Milano).

The technical literature also devotes considerable space to how the new plasters are applied to the lightweight drywall and fiberboard materials that began to make their appearance in those years. The literature makes a distinction between Eraclit drywall panels, and in general all types consisting of wood chips or magnesium cement, where thin coats of mortar are sufficient because of the high adhesion between the cellulose fibers and the plaster (and on which gypsum plasters show excellent performance), and those based on compressed fibers such as Insulite, Masonite, Celotex, and so forth, where it is advisable to use galvanized wire lath, and where the plaster reaches a thickness of around one centimeter. It was also recommended to cover panel joints with strips of hemp tacked at the intersections (a method of bridging gaps frequently referred to as «*a cavalletto*» in the handbooks of the period) and then plastered over.

To complete this brief survey of applying the new plasters to new materials, mention should also be made of the metal corner beads placed on outside corners of adjoining walls at the time they are plastered. One of the most widely used of these products was the «Titano» corner bead patented and marketed by the producer of Terranova plaster.

While the foregoing remarks apply in general to all of the «new plasters», it is perhaps worthwhile to dwell for a moment on the distinctive characteristics of Terranova, which, though not the most commonly used, was without doubt the most widely publicized. In the technical handbooks of the period, Terranova is described as a «factory tinted plaster based on rock-hardenable silicates and natural colorants produced in a wide range of different colors and shades, supplied in ready-to-use bags in three grain sizes: fine, medium and coarse». It is also classified by method of application, three common categories being «Scraped Terranova», «Sprayed Terranova» and «Troweled Terranova».

A case apart is that of «Hard-grain Terranova» which, unlike the other types which feature uniformly sized, compact grains —though grain sized differed according to type— is made up of silica compounds in graded grain sizes and is thus particularly luminous.

«Scraped Terranova» is applied to a base coat of lime, sand and portland cement in four separate operations: Application - Floating - Scraping - Brushing.

— Application is carried out using an ordinary plasterer's trowel, achieving a thickness of 5 to 7 mm.
— Floating is performed using an ordinary wooden float. As soon as the plaster begins to set, it is scraped down to a thickness to 5 mm.
— Scraping is performed using an ordinary chamfer-edged steel scraper.
— Finally, brushing is performed using an ordinary bristle brush.

The most delicate operation is scraping, as the success of the work depends chiefly on it.

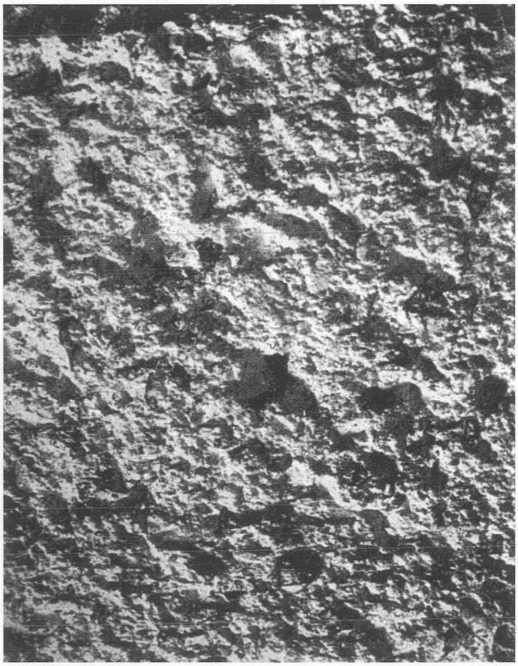


Figure 6
Examples of hard-grain Terranova in actual service, Marescotti, Felice. 1937. «L'intonaco Terranova a grana dura», *Casabella,* 110: 41

«Sprayed Terranova» is applied to a thickness of 3 mm using special machinery supplied by the plaster manufacturer, and requires that the underlying base coat be applied with greater care to avoid unevenness.

«Troweled Terranova» is simply troweled on without further operations.

Finally, «Hard-grain Terranova» is applied using normal plastering tools.

As regards areas of application, a distinction should be made between the types featuring constant grain size («Scraped Terranova», «Sprayed Terranova» and «Troweled Terranova»), which are used both on exterior and interior walls, and those with variable grain sizes (hard-grain Terranova), whose strength and resistance —being much higher than that of the other grades of Terranova— makes it advisable for walls or portions thereof that are subject to continual wear, and in particular for wall bases, stairwells, entryways, heavily trafficked areas, work areas and so forth.

Terranova and the test of time

After discussing the cultural climate that prevailed in the early years of Terranova plaster's life, it can be of interest to consider its relationship with time in the light of what Domenico Morelli saw as the «betrayal» on the part of materials.

Nor is Morelli alone in his sense of betrayal: the dramatic fragility of modern architecture has also been perceived by Marco Dezzi Bardeschi.

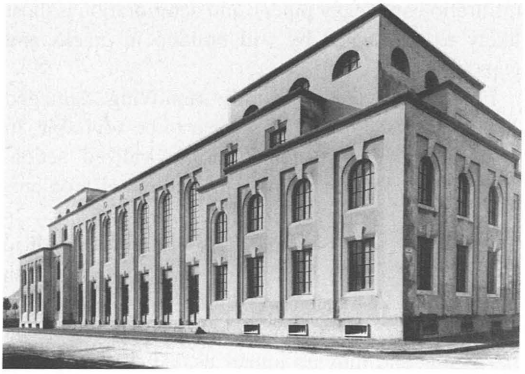


Figure 7
Costantino Costantini, 1929–1930. Casa del balilla. Torino
Casa bella, December 1931



Figure 8
Emilio Decker. 1932.
Building designed for the Compagnia Anonima d'Assicurazioni di Torino.
L'Architettura Italiana, October 1932

> The architecture of the Modern Movement is by its very nature eicastic, rarefied, almost dematerialized; it relies on pristine surfaces, so clean as to be peremptory . . . it manifests, proclaims an absolute idea that will dominate through its sheer, imperious force. But once translated into concrete shape, alas, it can do naught but follow the biological laws that govern its components (Dezzi Bardeschi 1986).

For a variety of reasons, in fact, be they formal (as in the case of certain design solutions such as flat roofs, walled balconies and facades shorn of projections), technological (as where materials were selected because they were «modern, domestically produced, experimental» even though nothing was known of their performance in service or over time) or ideological, such as the decisions stemming from a

machine-oriented aesthetics, we must admit that, however bitter such a realization may be, modern architecture is constitutionally and irremediable fragile: it deteriorates more quickly than its advocates and proponents had foreseen, and thus requires greater care and attention than the architecture that preceded it. For modern architecture more than for any other kind, it is thus fundamental to employ a cognitive approach pursued through a fuller analysis of case-histories. This type of approach, however, is «often neglected even for buildings that are part of our everyday knowledge, and about which we ought, in fact, to be able to find out much more» (Bardelli, Rome, 1992).

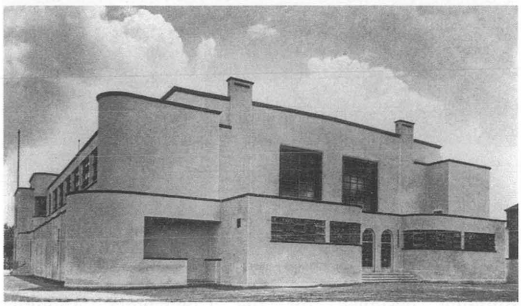


Figure 9
Contardo Bonicelli, 1929–1933. Indoor swimming pool at the municipal sports center.Torino.
L'Architettura italiana, September 1933

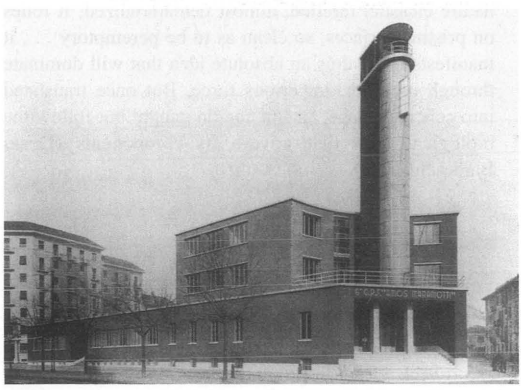


Figure 10
Giuseppe Canestri. 1937.Assembly hall, *Gruppo Rionale Fascista Amos Maramotti*
L'Architettura Italiana, January 1938

If these considerations apply in general to all of the materials associated with the poetics of Rationalism, it is essential to understand the inherent characteristics of Terranova plaster, the most extensively advertised of its day, if not the most widely used. If the success and survival of a material (Terranova, as we shall see, continues to be produced and used today) spring from its initial popularity, its technical and appearance-related characteristics, and, intimately connected to these characteristics, its performance in service and over time, then we can say that the features that did most to differentiate Terranova from other earlier or coeval plasters were the fact that it is factory tinted, applied in relatively thick coats, and reinforced with mineral fibers.

The latter features in particular have ensured outstanding technical performance, despite certain application problems. With spray processes, for instance, thickness is hard to gauge, particularly at joints.[4]

In addition, the fact of being a thick, high-build product helps mask imperfections and makes it possible to use one rather than two final scraping and decorating stages.[5]

As for how Terranova has stood the test of time, we can say that it has done very well on the whole. Throughout Italy, in fact, we find individual buildings or whole districts which still retain their Terranova plaster after sixty years and more, its colors, though dulled and at times even gloomy, as evocative as ever.

Terranova shows good adhesion to the underlying masonry (sagging, delamination and the like are usually due to water in the wall as a result of local infiltration and leaky pipes), and deterioration is most likely to be caused by soil buildup in cracks and gaps.[6]

For these reasons, totally removing damaged Terranova plaster does not appear to be advisable. In most cases, it is better to take localized action, cleaning the plaster, eliminating structural problems and patching where necessary.

As for the measures that have been introduced to bring the system up to date (an inevitable process in view of the new potential offered by manufacturing equipment), the asbestos fibers – now regarded as hazardous and thus no longer usable – added to the mixture in order to reinforce the plaster and prevent cracking have been replaced with other compatible, long-lasting fibers.

Terranova and its manufacturer

As indicated earlier, Terranova plaster is still being produced today, though it has been variously adapted to meet changing needs and new regulatory requirements. Thus, the history of this «new material» has, in reality, lasted over a hundred years. Consequently, a review of some of the most important moments of this history is perhaps not without interest.[7]

In 1893, *Terranova - Industrie C.A. Kapferer & Co.* began manufacturing prepackaged tinted plaster in Germany, and specifically in Freihung, Bavaria. Soon afterwards, the company's success enabled it to set up production units throughout Europe. Around 1920, Terranova products began to be marketed in Italy, imported from by Germany by Agenzia Sironi of Milano.

In 1932, the German parent company Terranova and the Milano agency headed by Aristide Sironi set up an Italian joint-stock company, S.A. Intonaci Terranova, headquartered in Via Benaco, Milano. Sprayed Terronova was employed for the first time in this period for the buildings housing the Milano Triennial (1940–1942).

In 1936, the plant in Via Stephenson 70, Milano, was inaugurated. This plant is still active today.

In 1939, the Civitavecchia plant was inaugurated, producing Teranova plaster for southern Italy and the colonies. The plant was shut down in 1956.



Figure 11
Advertisement
L'architettura Italiana, October 1936



Figure 12
Advertisement
Rassegna di Architettura, June 1937

In 1945, the SIRONI family bought out the German-held shares to set up a new, all-Italian company, SOCIETÀ ITALIANA INTONACI TERRANOVA. In the early 50s, the company's production included scraped Terranova, troweled Terranova, sprayed Terranova and hard-grain Terranova. In 1956, production of plastic-based products (the Ferdian Plast line) got under way, and these products were gradually introduced alongside mineral plasters.

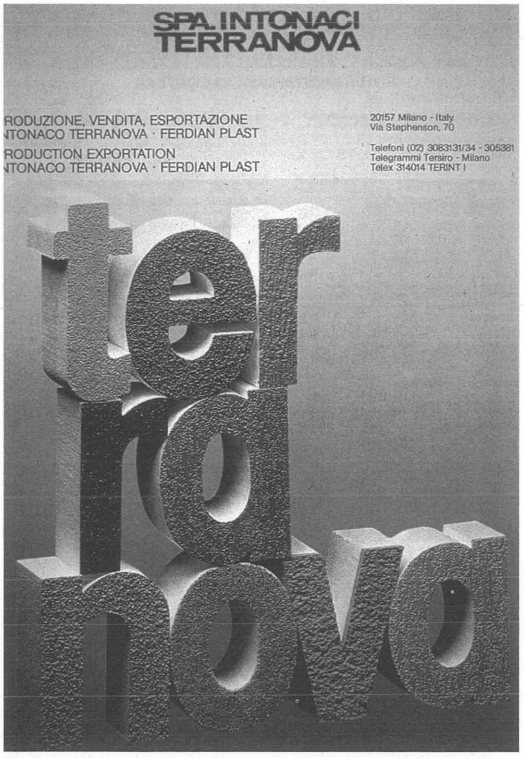
Between 1980 and 1985, silicate plasters were developed under the tradename Terrasil.

In 1987, the Austrian TERRANOVA unit bought 100% of the shares of SOC. ITALIANA INTONACI TERRANOVA, at the same acquiring full ownership of SOC. TERRANOVA throughout Europe. This was the same year that saw the introduction of Terrasan repair plasters and Terratherm insulating plasters.

In 1993, on its hundredth anniversary, TERRANOVA ITALIA sponsored the restoration of Casa *MALAPARTE* in Capri.

In July 1993, the Austrian TERRANOVA Group and all TERRANOVA companies controlled by it (in Italy, Germany, Hungary, the Czech Republic and Slovakia) were acquired by WEBER & BROUTIN of Paris, the leading European producer of ready mix tinted plasters for construction application. Under the new ownership, TERRANOVA continues to develop the plasters that made it famous. Once the name of the company, TERRANOVA becomes the name of the product.

Several of the products featured in the current catalog, including marbled Terranova, sprayed Terranova, and troweled Terranova, can be compared to the historical Terranova plasters, though they have been adapted to reflect more recent technical needs and market demand *(WEBER & BROUTIN* 1997).



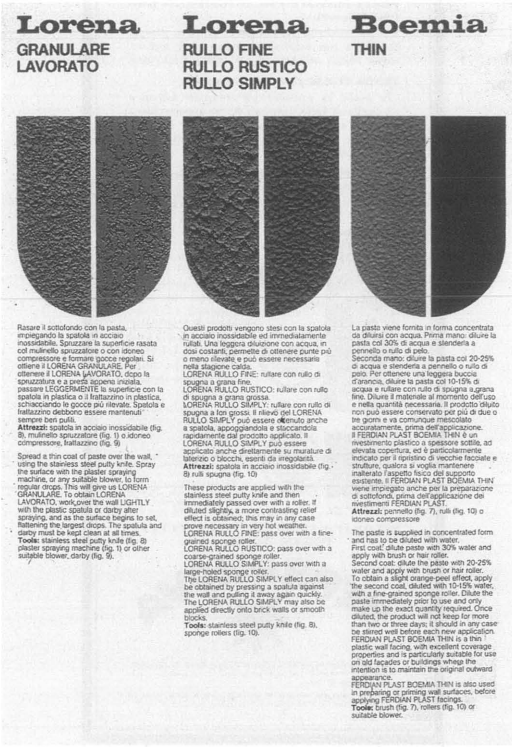


Figure 13–14
Advertising brochure, 1960s
(Weber & Broutin archives)

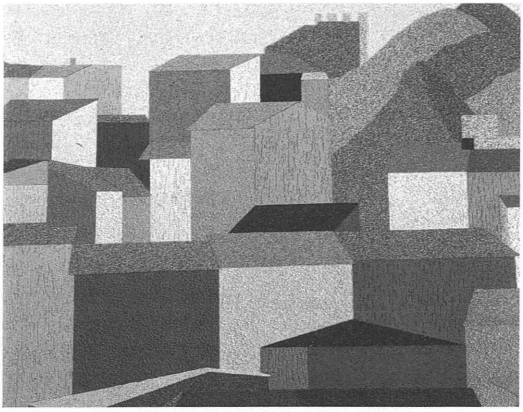


Figure 15
Promotional work produced using Terranova plaster by the painter Zapparoli-Sironi. (Weber & Broutin archives)

Notes

1. «Factory tinted» means that pigments were mixed into the product during production.
2. *Lincruster*: An interior trim material based on boiled linseed oil, normally spread on paperboard and in some cases on canvas. It was produced in three different types, smooth, imitation silk, and relief, with a wide range of patterns and shimmering iridescent colors of great decorative impact.
   Opaline glass: A type of glass tinted by mixing coloring oxides into the batch, so that the color is uniform throughout the thickness of the product. Sheets or tiles of Opaline glass were produced in three types: polished on one face, polished on both faces, and unpolished. At the beginning, only two colors – milk white and black – were available, as they were the only ones in high demand, given the striking decorative effects obtained by using them in combination. The color range was later extended to satisfy a larger variety of needs, particularly in interior decoration.
   Desagnat flexible glass: A patented product consisting of 50x50 cm sheets of glass with cuts in both perpendicular directions across the sheet to form a large number of tiny tesserae secured to a thin backing of strong fabric. These tesserae were colored and/or decorated on one of the two faces, and could move relative to each other so that the entire panel was perfectly flexible in both horizontal and vertical directions. Many versions were available, with mirror-finish or gilded surfaces, solid colors, and veined, streaked or marbled effects.
   Civer tiles: Tiles consisting of a special vitreous compound, perfectly smooth on one side and granular on the other. Their regularity and uniformity are similar to Opaline glass.
   For the characteristics of the new materials that were put on the market during the Twenties and their importance to architecture, see Garda (1991).
3. *Buxus*: A solid, elastic material with swirling, briar-like streaks obtained through a cellulose ossification process, and one of the most commonly used substitutes for wood in the Thirties. It was produced by the Giacomo Bosso paper mill of Torino in two different types: the soft-cured version (Corium) used for boxes, suitcases, etc., and true Buxus, used in all areas of architecture and interior decoration.
   On the use of Buxus as a «substitute» material, see Thea (1983); Garda (2000).
4. Problems resulting from incorrect application times, from allowing excessive or insufficient time between the first and second coats, and from insufficient thickness on the part of the underlying base coat are most obvious at the joints.
5. The further development of this concept, i.e., that of reducing the number of coats and thus cutting labor costs, led to the introduction of single-coat ready mix factory tinted products such as the «Monocappa» plaster which became particularly popular in France from the '80s onwards.
6. As regards weather resistance, it has been found that *Terranova* plaster holds up well under heavy rains, though frequent acid rain can interact with certain pigments and cause them to fade.
7. The following account of the company's history and its products was compiled with the help of Manfredo Barberis (Product Marketing —Manager, Technical Mortars and Repair Products Division— Weber & Broutin, Italy).

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Prestressing of 19th century wood and iron truss bridges in the U.S.

Dario A. Gasparini
Francesca da Porto

Many of the well-known American truss bridges built in the first half of the 19th century were prestressed. Specifically, the Long, Howe, Pratt and Rider/Moulton forms, built entirely of wood or iron or using a combination of wood and iron, were prestressed. The prestressing was achieved by driving wood or iron wedges or by tightening nuts on threaded iron rods. The level of prestressing was controlled only qualitatively, probably by observing if any elements became slack when a heavy live load traversed the span. The significant advantages of prestressing were that connections were simplified, some wood tensile connections were eliminated and, if all elements did not loosen, the stiffness of a bridge was increased.

This paper describes studies of the Eldean Bridge in Miami County, Ohio. The Eldean Bridge is a wooden Long truss, built in 1860 by James and William Hamilton. The experimental and analytical studies address the actual magnitudes of prestress forces achieved by driving wedges, the effects of prestress on the structural behavior, the loss of prestress from wood shrinkage and creep, and the need for periodic retightening. Also presented are studies of the Pine Bluff Bridge in Putnam County, Indiana. The Pine Bluff Bridge is a classic Howe truss, built in 1886 by Joseph Albert Britton. The studies quantify the actual magnitudes of prestress forces achieved by tightening nuts and examine the same issues as those for the Long truss.

After the Long and Howe trusses, two significant prestressed truss forms were patented in the U.S. They are the truss of Thomas and Caleb Pratt and the truss of Nathaniel Rider and Stephen Moulton. These designs are briefly discussed, to provide a more complete view of the early 19th century prestressed truss forms.

Stephen Harriman Long truss patents of 1830 and 1839

Gasparini and Provost (1989) and Gasparini and Simmons (1997) describe the

contributions of S. H. Long to the design of trusses. Long's understanding of truss behavior is perhaps best exemplified by his May 6, 1830 and November 7, 1839 (No. 1387) U.S. patents. Both patents show an ordinary St. Andrew's cross type of truss but one of Long's significant patent claims is for a system of wedges or «keys» for prestressing the trusses. Figs. 1 and 2 show details from his 1830 and 1839 patents, respectively.

Figure 1 shows a wedge driven at the end of a diagonal brace, thus prestressing both diagonals in compression and the verticals in tension. Writing in the Journal of the Franklin Institute, Long states that «the braces all act uniformly in the direction of their axes and exclusively by *thrust.* Their connection with the truss frames is such as to preclude any action by *tension*» (Long, 1830). Conversely, Fig. 2, from his

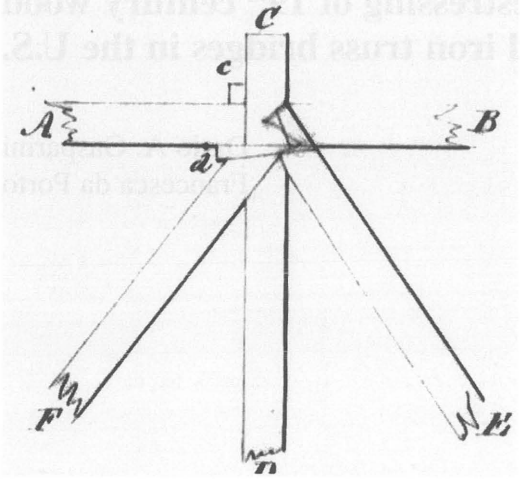


Figure 1
Wedge detail from S. H. Long's patent of March 6, 1830

1839 patent, shows wedges between the vertical post and the chord, thus precompressing the verticals and pretensioning the diagonals. In his 1839 patent description, Long states,

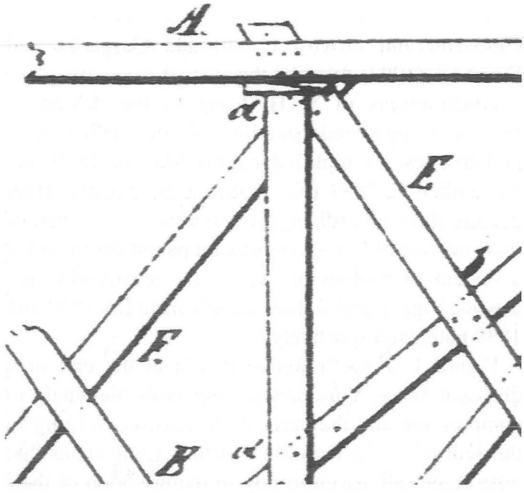


Figure 2
Wedge detail from S.H. Long's patent of November 7, 1839 (No. 1397)

> The straining, or trussing, of the truss frames is effected by driving the counter wedges, above mentioned, which are situated as shown in the drawing, between the upper end of each post, and the upper string-piece, but which may, if preferred be situated between the lower ends of said posts, and the lower string pieces. This operation is calculated to elevate the upper string, at the points where the main braces are attached to it; and of course to increase the tension of the main braces in the adjacent panel. Every increment of tension thus produced is counteracted by a corresponding degree of antagonal tension in the counter braces. Hence the main and counter diagonal braces act by tension instead of thrust, and the posts by thrust instead of tension (Long, 1839).

Of course Long could not quantify the prestress forces that were achieved and could not predict whether shrinkage and creep in the wood would, in time, loosen the wedges. However, it was understood that the wedges could be periodically re-driven. The objectives of the studies of the Eldean Bridge, which is of the Long type, were in fact to quantify the forces produced by driving wedges and to determine the effects of creep and shrinkage on these forces.

Studies of the Eldean Bridge in Miami County, Ohio

The Eldean Bridge over the Great Miami River, in Miami County, Ohio was built by James and William Hamilton in 1860. The bridge has two spans of Long trusses. It is the second longest covered bridge in Ohio and the longest Long truss covered bridge in the U.S. Under a contract with the U.S. Federal Highway Administration (FHWA), the Historic American Engineering Record (HAER) documented the bridge during the Summer of 2002. Analytical and experimental studies of the bridge were performed as part of the documentation. The full study is contained in HAER report number OH-122, which is to be archived in the Library of Congress.

The bridge is constructed of white pine, shipped from Michigan. The floor is made of American elm. The length of each span is about 33.8m; the overall width is approximately 6.4 m with a 5.5 m wide roadway. The trusses have twelve panels, each approximately 2.7 m wide. The sizes of the main diagonals and of the posts increase from midspan to the ends. The main diagonals are made of two timbers

that vary in dimension from 23 cm × 15.2 cm in the end panel to 15.2 cm × 15.2 cm in the central panel. The posts also are composed of two timbers that vary in dimension from 28 cm × 15.2 cm to 21.6 cm × 15.2 cm. All counterbraces have a cross-section of 12.7 cm × 17.8 cm. The cross-sectional areas of the upper and lower chords are 1290 cm^2 and 1420 cm^2, respectively. Chord splices are achieved by simple rectangular shear connectors, completely bolted through the chord. The prestressing wedges are located at the bottom of the counters. A wood plank is nailed horizontally to the posts in order to prevent the counterbraces from slipping inside the space between the two posts. This plank is located about 5cm above the lower chord, to allow driving the wedges in the slit. The bridge has had many repairs, which are described in HAER report number OH-122.

Analytical studies were performed using two linear elastic plane models, one with active (prestressed) counters and the other without them, as shown in Fig. 3.

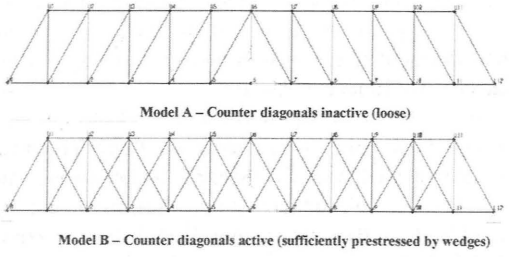


Figure 3
Linear elastic, plane models of the Eldean Bridge —Model A has inactive counters, Model B has active counters

The models were used to predict the effects of dead load, live load, prestressing, shrinkage and creep. Fig. 4 shows influence lines for three diagonal members for the model without active counters. A live load of 1 kN at panel point L5 produces an axial force in member L5U6 of 0.45 kN (tension). Dead load produces an axial force in the same diagonal equal to 11.4 kN (compression). Therefore by simple proportion, a live load of 25.3 kN applied at panel point L5; i.e., a total load of 50.6 kN applied to the entire bridge at L5, would cause diagonal L5U6 to

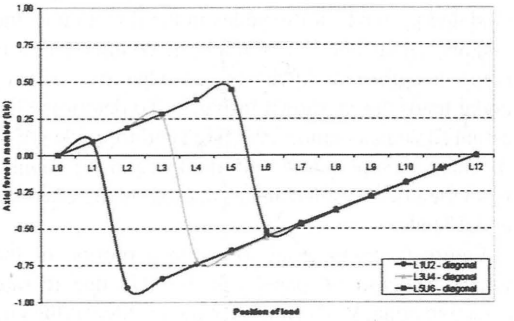


Figure 4
Influence lines for three diagonals for the model with inactive counters

become loose, since it is not positively connected at its ends. Again using the influence lines, it is further determined that a uniformly distributed load of 1.82 kPa over half of the span would also loosen member L5U6. With such a concentrated or uniformly distributed load, the structure would develop a kinematic mechanism if the connections were perfect pins. In reality, the joints of the actual bridge are not perfect pins, since the lower and upper chords are continuous. Because of this continuity, the bridge does not develop a mechanism, but it is clear that such loads produce a «limit state» condition for the structural behavior of the bridge. Prestressing the diagonals in compression increases the live loads that produce such a limit state.

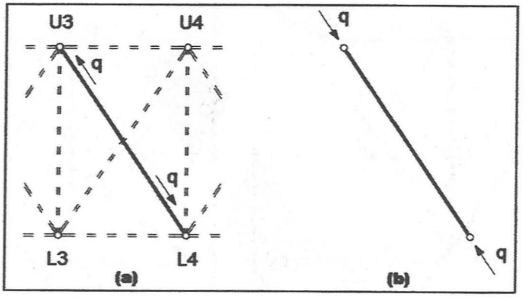


Figure 5
Effective nodal loads and fixed end forces from driving a wedge at the base of a counterbrace

The prestressing action of driving wedges is modeled by loads at the nodes in the direction of the diagonal elements. For example, if counter L4U3 is being «lengthened» by driving a wedge, the affective nodal loads are as shown in Fig. 5. To determine the actual force in a counter, the fixed end force shown in (b) must be superposed with the force in the counter from the nodal displacements caused by the effective nodal loads.

Figure 6 shows axial forces in a portion of the model centered on panel L3U3–L4U4 due to unit effective nodal loads from driving a wedge at the end of counter L4U3. In this example, counter L4U3 has an axial force of 0.43kN due to the effective nodal loads. Adding its fixed end compressive force of –1kN, its total axial compressive forces is –0.57kN. Conversely, both the posts and the chords are in tension. The forces in the vertical elements are comparable in absolute value to the forces in the diagonals. The chord forces are about half those in the diagonals. The relative values of the forces in the elements obtained by prestressing depend on the panel geometry. The effects of driving one wedge rapidly decrease to zero in other panels. In the two adjacent panels the magnitudes of the axial forces are ten times smaller that in the panel in which the wedge is driven. Therefore the prestressing action of driving a wedge is effective only in one panel, so to prestress an entire truss, all the wedges have to be driven. If this is done, the prestress forces are very uniform all along the span. In general, the combined actions of prestressing and live load lead to the following critical elements: the midspan lower chord element, where prestressing increases the tensile force, the most compressed main diagonal near the ends, and the counter with the largest tensile force from a live load, which thus has the greatest probability of having a null axial force. But in order to determine the live load that could cause loose counter diagonals, it is necessary to estimate the actual prestress force achieved by driving wedges.

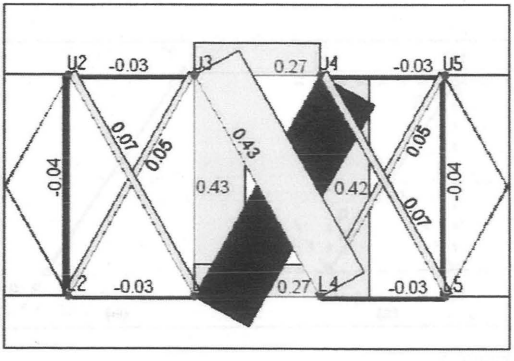


Figure 6
Member forces from unit effective prestressing loads

The shrinkage action is also modeled analytically by effective nodal loads given by $\varepsilon_s EA$, in which ε_s is a shrinkage strain, E is the modulus of elasticity and A is a cross-sectional area of an element. For the all-wood Eldean Bridge, if all elements are assumed to have equal shrinkage strains, the shrinkage action does not cause significant axial forces, not only in the model without the counters but also in the model with active counters. This observation is not true for creep since creep strains are approximately proportional to the initial elastic axial stresses, which are not equal for all members. Therefore creep produces changes in element forces in the model with active (prestressed) counters. To determine if and when creep causes looseness; i.e., complete loss of prestress, the initial prestressing forces from driving wedges must be known and analyses must be performed using viscous constitutive models for wood.

Experiments were performed on the Eldean bridge with the objectives of estimating the forces produced by driving wedges and comparing the behavior of the bridge in non-prestressed and prestressed conditions. Details of the tests are given in HAER report number OH-122. To measure forces produced by driving a wedge, fourteen strain transducers, as shown in Fig. 7, were attached on members of one panel. Four displacement transducers, one for each truss plane, were mounted at the midspans to measure overall bridge response to the passage of a truck.

Figure 8 shows forces (in pounds) in the diagonal and vertical elements produced by driving a wedge. The test was repeated twice, and the average force in the counterbrace was 26.8kN, compression. Since unit live load at node L10 produces a tensile force of 0.4 in counter L10U11, the live load at L10 that would loosen counterbrace L10U11 is approximately 67 kN, or 134 kN on the bridge. The live load required to loosen the diagonals near midspan is significantly larger than for the truss without active counters. However, the prestress forces produced by



Figure 7
Strain transducers attached to main diagonals

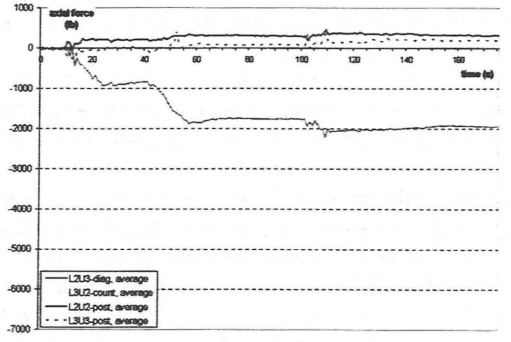


Figure 8
Member forces (in pounds) from driving a wedge

driving wedges are very likely not sufficient to preclude looseness under the action of creep, especially if it is assumed that creep strains are of the same order as the initial elastic strains. To determine the time at which looseness is likely to occur, analyses using viscous constitutive models for wood must be performed.

Figs. 9 shows time histories of midspan displacements from the passage of a truck weighing 35.2 kN, with no prestressing in either span. Fig.10 shows time histories of displacements with the eastern span prestressed. The constant displacement portions reflect the fact that the truck stopped at certain panel points. The spikes in displacement correspond to the truck accelerating from a stopped position. All tests show that when the truck is moving from the midspan position, L6, higher displacements are measured for load positions L8, L10 than for the corresponding ones on the first half of the bridge span (L4, L2). Also, when the truck leaves the span, a residual displacement, which slowly decreases to zero

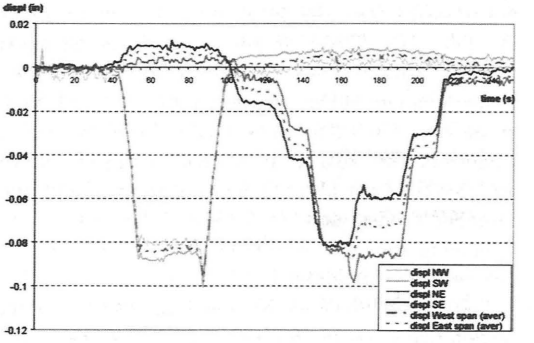


Figure 9
Time histories of midspan displacements (in Inches) from a moving truck load —counters inactive

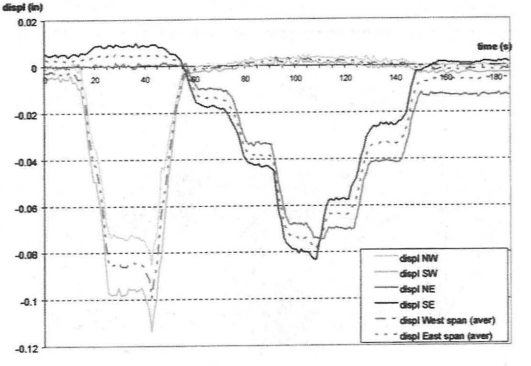


Figure 10
Time histories of midspan displacements (in inches) from a moving truck load —eastern span prestressed

with time, is observed. These observations strongly show that the stress-strain behavior of wood is time-dependent or viscous. After driving the wedges on the counterbraces of the eastern span, the measured displacements decreased by 12%. The wedges on the western span were not re-driven, so that the average displacement remained practically the same.

William Howe truss patents of July and August, 1840

Long's patents, booklet, and bridges, which were built throughout New England, were certainly known by and inspired another New England bridge builder, William Howe. Howe received two patents for prestressed bridges in 1840, one in July and another in August. His July 1840 patent was for an all-wood design, using wedges for prestressing, much like Long, although Howe used the wedges in a different arrangement. On August 3, 1840, Howe received a patent for the truss form shown in Fig.11. Howe replaced the vertical wooden posts with wrought iron threaded rods, and prestressed the bridge by tightening the nuts, a much simpler and effective process than driving wedges.

Perhaps unknown to Howe was the fact that Marc Seguin had used this form in 1824 for the stiffening truss of his Tournon-Tain suspension bridge (Seguin, 1826; Cotte, 1998). Howe's original patent shows diagonals that extend over two panels and an auxiliary tensile chord, located at the lower intersection of the diagonals. The detail used to transfer the rod tensile force to the diagonals is critical. If the transfer of force is by bearing perpendicular to the grain of the chord, crushing of the chord may occur. Moreover, shrinkage in the radial and tangential directions of wood is much greater than in the along-grain direction. Both crushing of the grain and shrinkage would cause a loss of prestress. Two critical improvements that allowed the Howe truss to become dominant in the U.S. in the period from 1840 to about 1870 were the use of diagonals that extended over only one panel and the introduction of iron node castings with webs that extended through the chord in order to transfer the rod axial force directly to the diagonals, eliminating bearing stresses perpendicular to the grain of the chords. It is uncertain who devised these improvements, perhaps Howe, perhaps his contractor brother-in-law, Amasa Stone, who built some of the earliest Howe trusses in New England. Beginning in 1845, all-iron Howe trusses began to be built by Richard B. Osborn, Frederick Harbach and Amasa Stone (Gasparini and Simmons, 1997).

Studies of the Pine Bluff Bridge in Putnam County, Indiana

The Pine Bluff Bridge over Big Walnut Creek in Putnam County, Indiana

was built by Joseph Albert Britton in 1886. The bridge is a classic Howe form, with threaded vertical wrought iron rods and cast iron nodes. The bridge consists of two simply-supported spans. Each truss is divided into ten panels, approximately 3m in length. The wood species used for the Pine Bluff Bridge was not determined, but the majority of the covered bridges in Putnam county are made of Michigan pine,

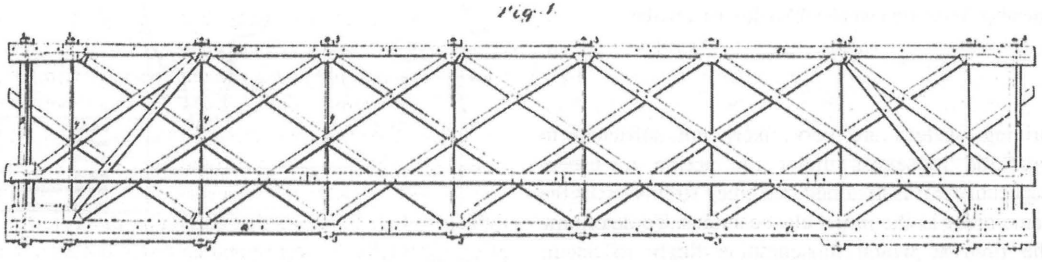


Figure 11
Howe truss drawing for his August 3, 1940 U.S. patent

which is a type of white pine. In its present condition, practically all the counterbraces are loose and, since the vertical members consist of pairs of wrought iron rods, the individual rods are clearly not equally loaded and, in fact, some are almost slack. The bridge truss therefore essentially behaves as a statically determinate truss with single (compressive) diagonals which are not positively connected to the chords. It is only the action of the dead load that prevents the single diagonals near midspan from becoming slack when a heavy live load traverses the span. The present condition of the bridge indicates that current maintenance practices do not recognize the original technology of the classic Howe truss.

The Pine Bluff Bridge was also recorded by HAER during the summer of 2002. As part of the documentation, analytical and experimental studies similar to those performed for the Eldean bridge were carried out. HAER report number IN-103 describes the studies. The analytical models used for the Pine Bluff Bridge are analogous to those shown in Fig. 3, except the Pine Bluff models have ten panels rather than twelve. Of course the geometry and member properties are different.

Analyses of the non-prestressed model were performed for the action of the actual dead load and for a unit live load traversing the span. On the basis of these analyses, it is found that a live load of 29kN applied at node L4; i.e., a total load of 58kN on the bridge, makes member L4U5 loose. As for the Eldean Bridge, such a load would produce a kinematic mechanism in the bridge if all joints were perfectly pinned. Because of the continuity of the chords, a mechanism is not formed, but nonetheless such a load represents an important limit state at which a change in the behavior of the bridge occurs.

Effects of the action of tightening the nut on one vertical are shown in Fig.12 for unit effective nodal loads from prestressing. The total force on element U3L3 is found by adding the fixed end force, which is assumed to be 1kN. The prestressing action affect only the two adjacent panels. The actual distribution of axial forces is, of course, a function of the aspect ratio of the panels. If all the vertical rods are tightened equally, practically uniform initial force conditions are achieved along the entire span. To determine how the effects of prestressing combine with the effects of dead load and live load, the actual forces achieved by tightening the nuts must be determined.

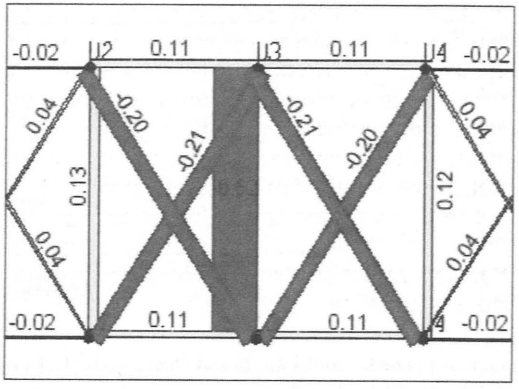


Figure 12
Member forces from unit effective prestressing loads

The effects of wood shrinkage on a Howe truss are very different from the effects of shrinkage on a Long truss. This is so because the iron rods do not shrink. Shrinkage of wood members in a Howe truss in fact reduces prestressing forces significantly and may cause the counters to become loose. Additional shrinkage after the counters become loose causes additional displacements but no further changes in forces because the truss has become a statically determinate form. Although the magnitudes of the changes in forces may differ, the effects of creep of wood on initial prestress forces are similar.

As for the Eldean Bridge, experimental studies were performed to determine the actual prestress forces that could be achieved by *manually* tightening the nuts. Strain gauges were bonded to the iron rods and strain transducers were attached to the wood members as shown in Fig. 7. An «inside» rod that was practically slack was selected for retightening. Figs. 13 and 14 show time histories of forces induced on the inside and outside rod and on the wooden diagonals as the nut was tightened. The actual maximum force induced in the rod by *manually* tightening the nut was approximately 29.4kN. At present, the actual size of wrench and method used by the original builders to tighten the nuts is unknown. Fig. 13 shows that the force in the *outside* vertical bar actually decreases as the *inside* rod is tightened. Fig. 14 shows that tightening the inside rod affects primarily the corresponding inside timber of the main diagonal. Therefore any pair of vertical rods should be tightened in stages in order to achieve equal

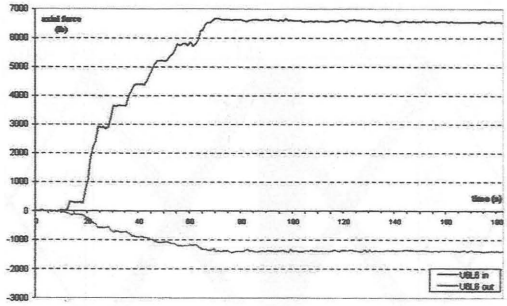


Figure 13
Forces (in pounds) on the inside and outside rods produced by tightening the nut on the inside rod

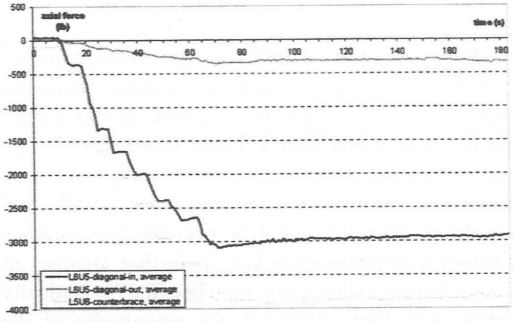


Figure 14
Forces (in pounds) on the diagonal members produced by tightening the nut on the inside rod

forces in members. It was not possible to «slacken» and properly pretension all the vertical rods on the Pine Bluff Bridge. Therefore the condition of the bridge remained such that most counter diagonals were loose and some vertical rods were slack. Therefore, in actuality, the bridge in its current condition is not a truly symmetric structure. Nonetheless, to determine the actual stiffness of the Howe truss, two displacement transducers were mounted at midspan, one for each truss, and a truck weighing approximately 53.4 kN was driven across the span. Fig. 15 shows the time history of midspan displacement. Constant displacement lines again reflect that the truck was stopped at certain nodes. These displacements were correlated with analytical predictions using the non-prestressed model. Details of the comparison are given in HAER report number IN-103.

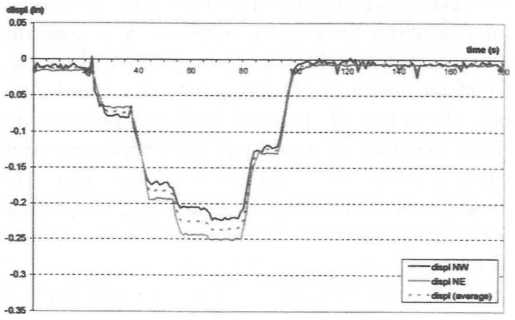


Figure 15
Midspan displacements (in inches) from a truck traversing the span

«Suspension» trusses

Long's 1830 patent truss and Howe's truss are prestressed to place the diagonals in compression and the verticals in tension. Prestressed truss forms that cause tension diagonals and compressive verticals were also conceived. Such forms, which were sometimes called «suspension» trusses, are described by Gasparini and Simmons (1997). Two basic techniques were used to achieve the desired behavior. Long (in his 1839 patent shown in Fig.2), Nathaniel Rider and Stephen Moulton used wedges on the vertical members while Thomas and Caleb Pratt prestressed by tightening nuts on threaded iron diagonals. The Pratt's introduction of threaded iron diagonals, as shown in Fig.16, was analogous to the simplification introduced by Howe to Long's 1830 patent. The Pratt truss required no positive connection between the chords and the verticals, which were prestressed in compression. Their patent description, which prescribes a method of erection, emphasizes that fact. The Pratt form is more efficient than the Howe form because the longer members (the diagonals) are in tension. Nonetheless, the design was not immediately successful, becoming dominant only in the 1870's in its nonprestressed, single-diagonal form. Its slow acceptance was probably due to its less-than-satisfactory performance when wood was used for the

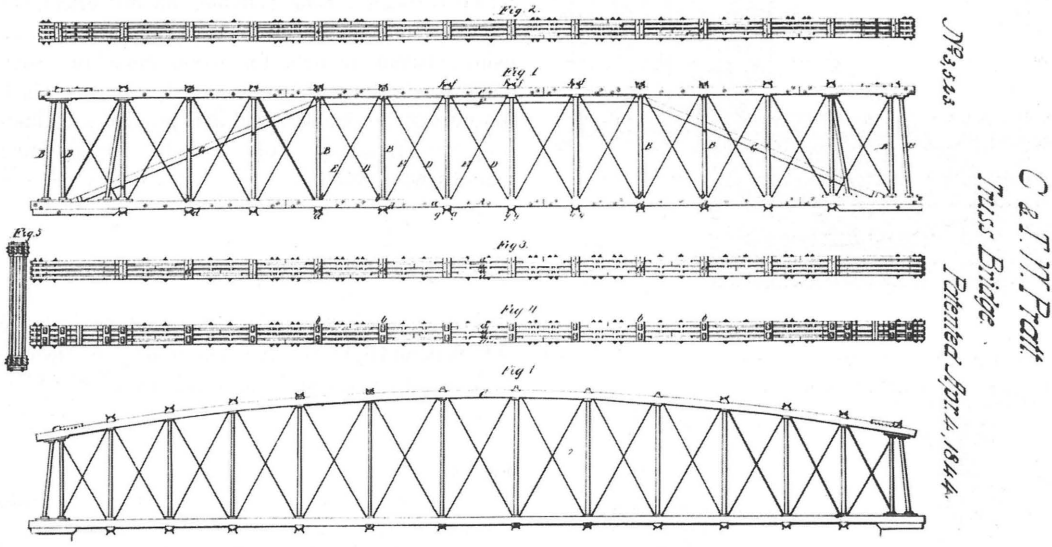


Figure 16
Truss patented by Thomas and Caleb Pratt on April 4, 1844 (No. 3523)

chords and for the vertical elements. In comparison with the Howe truss, twice as many rods had to be tightened; moreover, the nuts were in an awkward inclined position and were more difficult to tighten. Additionally, the prestress forces probably caused some local crushing of the wood chords, which led to a loss of prestress and decreased vertical stiffness. Further, from a stress viewpoint, the prestressing increased the compressive forces in the top chord, which, in turn, increased the risk of buckling.

An all-iron «suspension» truss was patented in the U.S. by Nathaniel Rider in 1845 and then by Stephen Moulton in England in 1847. It was a truss prestressed by wedges, as shown in Fig.17, precisely as Long had done for his 1839 patent truss. Because prestressing by wedges was awkward, the Rider/Moulton trusses were built only for a relatively short time. Still they represent an alternate way of achieving prestressed tensile diagonals.

Conclusions

The 19th century truss forms patented in the U.S. by S. H. Long, W. Howe, T. Pratt, N. Rider/S. Moulton were all intended to be prestressed. This is evident from their patent descriptions, from their use of «non-positive» connections and from executed designs. Of course, the prestress forces were not quantified. Nonetheless, prestressing simplified connection details, facilitated erection and added stiffness to bridges.

Studies of the Eldean Bridge, a Long truss, indicate that driving wedges can induce forces in the counters of approximately 26.8kN. Driving a wedge induces forces in only one panel. Equal longitudinal shrinkage of all the wooden members does not cause significant changes in member forces for a simply-supported truss. Conversely, creep, which is a function of initial elastic stresses, does cause a decrease or even a complete loss of prestress. Therefore periodic retightening of the wedges is very likely required.

Studies of the Pine Bluff Bridge, a Howe truss, indicate that *manual* tightening of a nut can induce forces in the vertical rods of approximately 29.4kN. Analyses show that tightening a vertical rod causes forces only in adjacent panels. Because the iron rods do not shrink, both longitudinal wood shrinkage and creep cause decreases or even a complete loss of prestress.

The current conditions of the two bridges that were studied indicate that indeed effects of shrinkage and

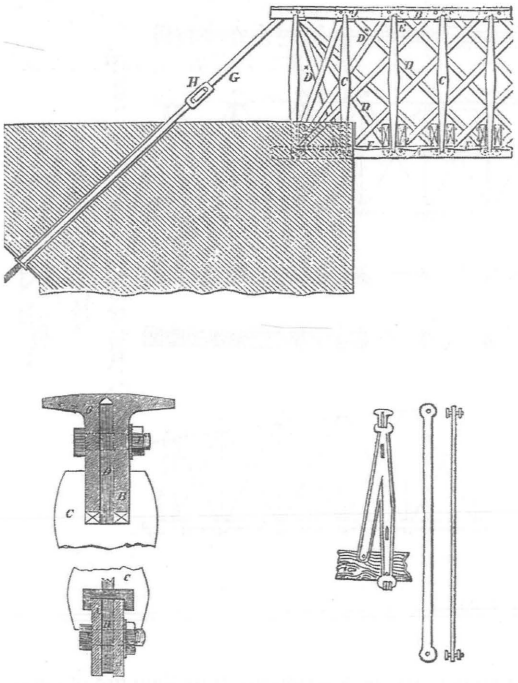


Figure 17
Truss patented by Nathaniel Rider in 1845 (No. 4287)

creep can reduce prestressing forces to zero. They also indicate that periodic retightening, which probably was the norm when the bridges were new, has not been part of current maintenance. It seems that this prestressing and retightening technology developed in the 19th century has been forgotten. It is both a historic and structural necessity to re-establish this prestressing technology, for both maintenance and new designs, using modern means for controlling prestress forces. Understanding of the effects of shrinkage and creep needs to be improved by analyses using viscous models for wood behavior. Such analyses can be used to establish rates at which prestress forces decrease and thus provide guidelines for the frequency of periodic retightening maintenance operations.

Acknowledgements

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New light on specialized XVIth century construction techniques in the Low Countries

Piet Geleyns
Krista De Jonge

The following paper briefly discusses two specific fields in construction in the 16th century Low Countries, foundation techniques on the one hand, waterproof mortars and masonry on the other. Primary sources for these subjects are the writings of two late-16th-century Netherlandish authors with great experience in these matters. Charles De Beste, a master-mason living in Bruges at the end of the 16th century, passed on his knowledge in an extensive manuscript called *Architectura*, conserved today at the Royal Library in Brussels (De Beste 1599; Van den Heuvel 1995). In this document, containing over 580 folios, the Fifth Book especially is of interest to those working in the field of construction history. This '*Boeck 5 tracterende van Architecturen ofte Bauwinghe*' manifestly refers to Vitruvius, but it also includes remarks and passages based on De Beste's own practice and on the architectural context of late 16th-century Bruges. Simon Stevin, Netherlandish scientist and engineer, was born in Bruges in 1548. He entered the service of Maurice of Orange at the end of the 16th century, and taught at the first military academy in The Hague. Stevin was a very prolific writer; several of his writings on a variety of subjects were published during his lifetime, but also posthumously by his son (Van den Heuvel 1994).[1] One specific manuscript, the so-called ‚*Huysbou*', is of particular interest to us. However, it was never published as such, and we only know it today through extensive references and quotations, included in the early 17th-century journal of Isaac Beeckman[2] (De Waard 1942).

To complement the information offered by these treatises, contemporary building records and related documents for a variety of buildings have been taken into account as well.

Foundation Technology

The Fifth book in the manuscript of Charles De Beste includes an entire chapter on foundations, '*Van het legghen der fondamenten*', providing us with a fine summary of the state of the art of foundation technology at the end of the 16th century, at times with surprisingly great similarity to what Vitruvius wrote more than 1600 years earlier (Gwilt 1826, III; Vitruvius Pollio and Rose 1899, III).

De Beste states that as a rule, foundations have to be dug until good soil is reached, preferably going one foot deeper since the upper part of this good soil is generally of lesser quality. These foundation structures will have to be at least one third wider than the walls that will be erected on top (De Beste 1599, f° 343^{r}–344^{v}). De Beste strongly disagrees with building masters who disregard the shape of the building when planning the foundation structures. In this regard, de Beste refers to the belfry of Bruges, an 8-sided tower, which apparently has a square foundation system (De Beste 1599, f° 344^{v}).

Where good soil is not available at acceptable depths, builders will have to reach for other techniques: De Beste extensively describes a

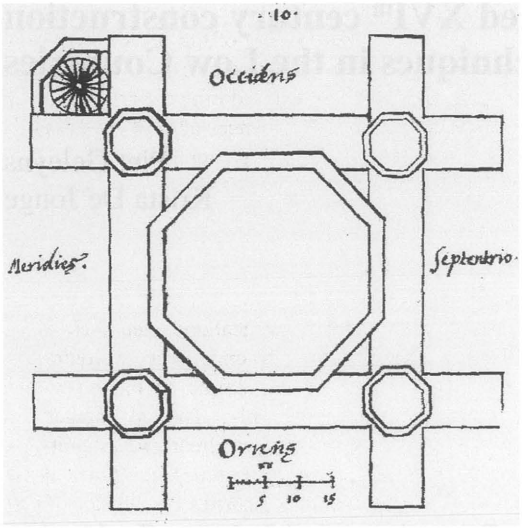


Figure 1
A sketch taken from De Beste's *Architectura*, showing the square foundation scheme and the eight-sided superstructure of the belfry of Bruges. (De Beste 1599, f° 344^{v})

procedure for pile-drilling,[3] which was probably very common in Bruges. He suggests using oak, but alder or oleaster would do as well. These trees were to be cut to piles with a square section and a pointed head, their length being at least ten times their diameter. When necessary, a metal pin should be fixed at the head of the pile, for example when the soil is rich in cobblestones. To improve the durability of the wood when sunk below ground, the surface of the piles could be burnt prior to drilling, a technique also mentioned by Vitruvius (Gwilt 1826, I: 5.3; Vitruvius Pollio and Rose 1899, I: 5.3). These piles would be placed closely against each other, the open spaces in between to be filled with ashes or charcoal. On top, massive oak planks would be fixed with copper nails, linking the piles together and providing a platform to start the foundation brickwork. This foundation technique is clearly illustrated by De Beste's contemporary, the architect and military engineer Pierre Lepoivre, in a drawing dated November 20, 1601, which shows the foundations of the (never to be built) north towers of the Arenberg Castle at Heverlee, then property of Charles II of Croÿ, duke of Aarschot (Duvosquel 1987, 76–79; Minnen 1993, 204–205 ill. 57).[4] As an alternative for piles, De Beste describes sinking stones until good soil is reached, but he warns that stones tend to float up due to the high ground water pressure. Certain lime stones, however, seem to be less subject to this side effect, according to De Beste because they soak up the water.[5]

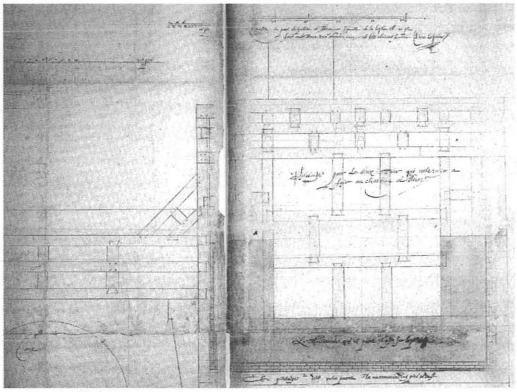


Figure 2
Design by Pierre Lepoivre of the pile foundations for the square corner towers of the Arenberg Castle. The drawing carries the following inscription: «Pylotaige pour les deux tours quy reste encor a fayr au chastiau de Hevre». KUL AA 2454.

The preserved building accounts for the construction of a new castle at Schoonhoven near Utrecht, some 150 km to the northeast of Bruges, give an even more accurate image of the practice of pile drilling in the Low Countries around 1525.[6] The castle, commissioned by the emperor Charles V himself, was built by the well-known Netherlandish building master Rombout Keldermans the Younger (Leys 1987, 163–165). Prior to the start of foundation work, thorough research of the characteristics of the soil was executed. As to the pile drilling itself, beech and willow were used, with pointed heads to facilitate drilling. On top of these piles, a wooden 'floor' was constructed, on top of which the foundation brickwork was set. The foundation structures were made with a lime-trass mortar, which will be discussed later on.

De Beste's overview also includes the technique of foundation pillars linked with arches, a technique

which was quite well-known in the middle ages, as remaining fragments of medieval city walls in Ghent, Brussels and Leuven still show today. According to De Beste, this was a very economical foundation technique: only the foundation pillars reached the depth where good soil could be found, the space in between the pillars was filled with rubble and sand, with an arch-shaped silhouette at the top, so that the arches linking each pair of pillars could be constructed without the use of centering. The irregular shape of these arches, visible on preserved examples, confirms this construction method.

Another paragraph in De Beste's chapter on foundations deals with contemporary fortification technology: De Beste claims that the overall stability of curtain walls and the supporting buttresses would be increased if wooden planks were incorporated in the foundation structures. Again, he suggests using oak, burnt preventively on the surface or coated with tar. In view of the introduction of these wooden pieces, the bricks for the surrounding brickwork were not to be wet before bricklaying, and the mortar had to be based on lime from limestone.[7] De Beste suggests that this part of construction was executed preferably in September, since this was the time when the ground water table was at its lowest. Traces of wooden reinforcements, or indeed of a complete wooden raft underneath the foundation walls, were found at Boussu castle, a work of the architect Jacques Du Broeucq for the imperial Master of Horse Jean de Hennin-Liétard, started in 1540 (De Jonge 1998a, 117). For special constructions such as towers, that are subject to relatively higher strains within the foundation masonry, De Beste suggests that every five layers, a diagonal layer would be incorporated, to improve the overall stability of the brickwork.[8] This bond was found in Jülich (Germany, close to the Belgian and Dutch borders), during the restoration of the 16th-century citadel defences after World War II, the brickwork probably going back to the second half of the 16th century (Geleyns 1998).

Various uses of Trass

Trass, as mentioned in historical documents related to Netherlandish building practice, was a hydraulic binder of volcanic origin, similar to the puzzolani found in the south of Italy. The advantages of hydraulic mortars were known already in antiquity — Vitruvius mentioned ground stones or gravel as an additive to improve the properties of mortars: «If to river or sea sand, potsherds ground and passed through a sieve, in the proportion of one third part, be added, the mortar will be better for use». However, by adding a certain volcanic material, Vitruvius claimed that mortars could be obtained that were even more durable, mortars that could even set under water. He dedicates an entire chapter in his Second Book on building materials to what we know today as natural cements:

> Est etiam genus pulveris quod efficit naturaliter res admirandas. Nascitur in regionibus Baianis et in agris municipiorum quae sunt circa Vesuvium montem. Quod commixtum cum calce et caemento non modo ceteris aedificiis praestat firmitatem, sed etiam moles cum struuntur in mari, sub aqua solidescunt (Vitruvius Pollio, M. and Rose 1899, II: 6.1).[9]

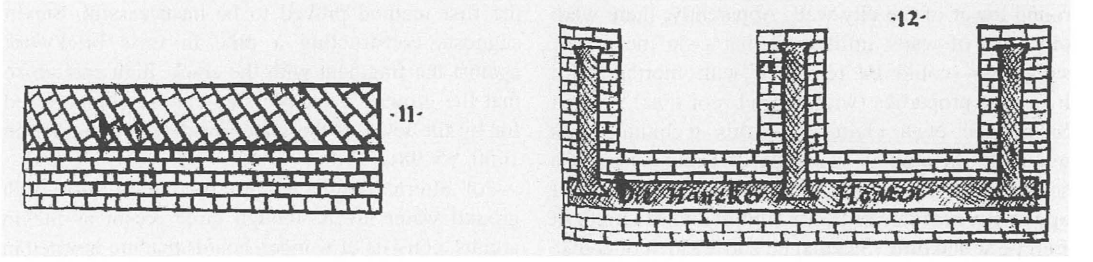


Figure 3
Two sketches taken from De Beste's chapter on foundations. The drawing on the left refers to the specific diagonal bond, the drawing on the right clarifies De Beste's suggestion to improve the connection between curtain walls and buttresses with wooden planks. (De Beste 1599, f° 345^{r})

This was common knowledge in late 16th-century building practice in the Low Countries, as we can read in Charles De Beste's treatise. He discusses both regular mortars with added powder of ground roof tiles or ceramics,[10] and hydraulic mortars. De Beste gives an almost literal translation of the passage found in Vitruvius, but adds that this 'puzzolan powder' described by Vitruvius cannot be found everywhere. However, there is a comparable material called trass stone, De Beste continues, which can be found in volcanic regions in nearby Germany, and which is a recent discovery according to him.[11] This trass stone has to be ground and sifted carefully, after which 2 parts of trass can be mixed with 3 parts of good lime to make a hydraulic mortar (De Beste 1599, f° 338r–338v).

In De Beste's own words, trass had been discovered 'fairly recently', which we should probably understand as 'dating from the 16th century'. This discovery runs parallel, in fact, to the introduction of several innovative solutions in the architecture of the Low Countries —the pile foundations at Schoonhoven are a good example of this. Even Thomas More included the following detail in his visionary Utopia of 1516, of a rather specific roof-rendering: « . . . Their roofs are flat, and on them they lay a sort of plaster, which costs very little, and yet is so tempered that it is not apt to take fire, and yet resists the weather more than lead» (More 1516, II: 'Of Their Towns, Particularly of Amaurot'). The pseudo-hydraulic mortars described higher, based on gravel and ground earthenware, however were already known in the southern Low Countries in late medieval times. For instance, in 1429–1430 repair works were executed in Mons, in the province of Hainaut, on the Tour Valenciennoise, a massive, round tower of the city wall. Apparently, there were problems of water infiltration that —so the source suggests— could be remedied with mortars with hydraulic properties (with ground roof tiles).[12] Alain Salamagne even claims that this technique was gradually diffused in the north of Europe from the second half of the 15th century onwards, while it apparently was already quite common in the south of Europe at that time (Salamagne 2001, 81): it of course has antique roots.

Simon Stevin, who like De Beste originated from Bruges, refers to trass on a number of occasions, for various uses. As a general remark with regard to the properties of the material, Stevin writes that trass sets in water, provided that this water is not running constantly. Under water, setting apparently takes roughly six weeks, whereas under normal conditions, trass mortars take two weeks to set.[13]

Obviously, the majority of Stevin's remarks on trass will relate to cellars, that part of the building where water often constitutes a constant and persistent problem. Stevin strongly favoured the construction of basements, provided that they were not moist (taking into account both ground water as well as rising damp) —otherwise, storing goods and food would be impossible, and the dampness would rise to the rooms overhead, which would strongly reduce living quality in that part of the house as well (Stevin 1650, 95–98). To meet this requirement, Stevin included a few construction techniques, the first based on trass mortar and sintered brick (*'clinckaert'*), ideally making up an impenetrable brickwork structure. Elsewhere, Stevin described more in detail a more specific procedure using trass: «To make basements in trass, one should lay a bed of sand first, followed by a bed of lime, on which *'dropsteen* (?)' is to be laid in trass, seven stones high, with a fourfold isolating layer of trass.[14] Stevin is well aware that cracks or holes in trass masonry are problematic, and offers two possible solutions. The first is a recipe for some sort of pap or slurry to close cracks in trass masonry, through which water would be dissipating; it is based on milk products.[15] This is not a unique occurrence at that time: mortar based on Brussels cream cheese was thought to be especially fitting for grotto work, because it was resistant to the water sprayed by the automatons (De Jonge 2000, 92–93; 101 n. 25).[16] In more urgent cases, with a higher ground water pressure for example, or when the first method proved to be unsuccessful, Stevin suggests constructing a pipe in trass brickwork against the fragment with the crack, high enough so that the ground water pressure can be compensated for by the level of the water inside the pipe (Stevin 1650, 95–98).

An alternative technique for areas with high ground water levels, though quite recent as Stevin admits, consists of wooden boards that are inserted in the ground, at least for the area that suffers from ground water. To resist the water, the planks are coated with tar and moss, «like caulking a ship» (Stevin 1650, 95–98).[17]

The use of trass in 16th-century construction to prevent water infiltration seems logical in the field of foundations and basements. Moreover, trass mortars also provided a good alternative for lead, as a covering for terraced roofs, and thus played an important role, it seems, in the introduction of large roof terraces and open-air galleries. These elements were important features of the innovative new architectural types of residential castles and prodigy houses, as will be explained by the examples of Mariemont (Hainaut) and Diest (Brabant) discussed below.

Work on the house at Mariemont, commissioned by Mary of Hungary, regent of the Low Countries, started in 1546. Together with its gardens, it was devastated by the French in 1554 already, and restored from 1555 till 1560 by its architect Jacques Du Broeucq. At the close of the 16th century, however, it had again fallen into disrepair; Albert of Habsburg, and the Infanta Isabella of Spain restored it again (1598–1620), adding the corner pavilions and several large wings to house their entourage (Wellens 1958–1961; Demeester 1978–1981). Nothing remains of it today.

As with the English prodigy houses, the architecture of Mariemont plays an important role in establishing the prestigious nature of the complex, aiming at a sensation of amazement and enchantment. In view of its role as backdrop for courtly events and hunting parties, the interaction between architecture and landscape was of paramount importance. This led to the creation of elaborate terraced gardens and parks, with belvederes and galleries serving as transitional spaces between the residence and its immediate surroundings (De Jonge 1998b).

Building accounts and iconography —although mainly 17th-century, these images accurately represent the 16th-century core —enable an accurate reconstruction of the original situation. The 16th-century house was a more or less cubic volume, measuring circa 19m on each side, but contrary to what later iconographical sources suggest, it initially did not have a sloping roof.[18] This cube was placed in the exact centre of a water basin of 35m by 37m, construction of which was quite a technical achievement since it had had to be in part dug out of the steeply sloping hill on which the house was erected. This was the work of Guillaume Le Naing, master mason of Binche.[19] On the southward and westward sides, impressive retaining walls can indeed be seen in the earliest views, the most accurate of which were painted by Jan Brueghel the Elder.[20] Both the roof-terrace and the water-retaining walls were at the time quite unusual, not in the least due to their scale. To secure a waterproof finish, the basin-walls and floor, including the basement walls of the castle on the inside of the basin, were covered with a dense clay, a technique which was well-known at the time from infrastructure works and hydraulics.[21] The original roof terrace was covered with lead, possibly also with clay as an extra waterproof layer underneath.[22] The roof terrace never proved to be completely waterproof, however, as can be deduced from the fact that in 1567, only a short time after the first repairs, it was covered with a sloping roof by Du Broeucq himself.

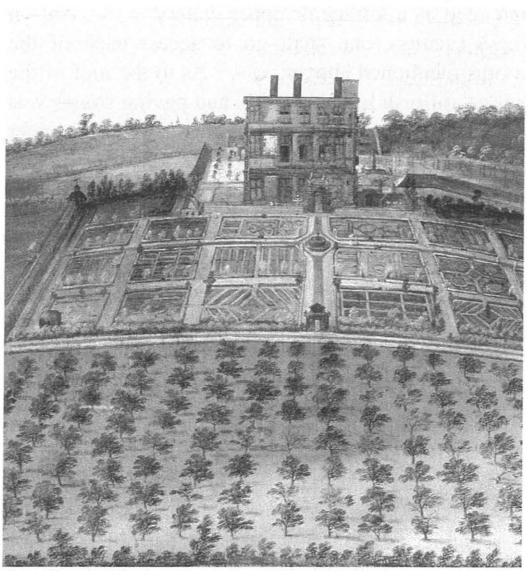


Figure 4
Digitally reworked image showing the putative 16th-century state. Jan Brueghel the Elder, 'Mariemont seen from the south'. 1612, Dijon, Musée des Beaux Arts. Inv. nr. CA102.

A preserved builder's estimate for the new residence in Diest commissioned by Henry III, count of Nassau, testifies to the fact that trass was a well-known additive already in the 1530's —the estimate,

and the (lost) design to which it corresponds, presumably date from ca. 1530–1538. However, the castle was never executed. A reconstruction made by Bernhard Roosens (1983) shows a quadrangle, with two stories above the ground floor and the vaulted cellars, and with round staircase towers protruding at the angles. In front of each wing ran a portico on the courtyard-side, with a terraced roof. This design is closely related to similar noble residences dating from the first half of the 16th century, all with a regular square or rectangular plan and a portico in the courtyard (De Jonge 1998a, 161–187). Other examples are Henry III of Nassau's castle at Breda, construction of which was started in 1536, and the palazzo in fortezza in Jülich, residence of Willam V, duke of Jülich-Kleve-Berg, started in 1549.

The arched gallery on ground floor level was vaulted with a trass-mortar. The document states explicitly that the roof of the gallery itself was also intended as a terrace or upper gallery: « . . . and on these (vaults), one shall go to access each of the rooms mentioned above . . . ».[23] As to the roof of the wings, a finish based on trass and paving stones was intended as a first variant, the vaulting of the upper floor underneath also to be executed using a trass mortar.[24] Combined with the summer house to be built on the roof, this would provide the perfect setting for banquets in good weather —the designer(s) even included the possibility to install a fishing pond on the roof.[25] Using roofs for banquets was not so unusual in the world of English prodigy houses, as for example at Longleat; records discussing construction work around 1570 inform us that «Item all the stares to Ryse above the howse and to be types, and IIII to have lytle stares wonne fro the roofe so as they may as banketting howses».[26] Nevertheless, the designer(s) at Diest included an alternative solution for a sloping roof in the same document, which indicates that they were aware of the rather ambitious nature of their design, marking it as something still rather unusual in the Netherlandish building tradition.[27]

Isaac Beeckman's 'Journal' includes remarks by Stevin, which offer a succinct overview of the problems inherent to terraced roofs such as these:

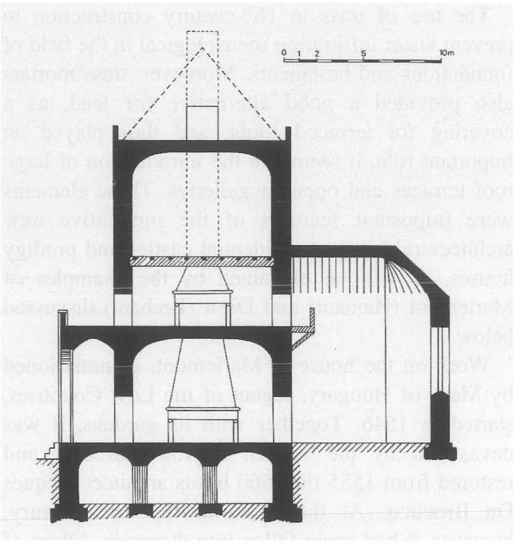


Figure 5
Two drawings of the Castle at Diest, made by Bernhard Roosens based on the descriptions in the builder's estimate. The section on the left gives an idea of the open air portico and the roof terrace —the dotted lines present the alternative with a sloping roof (Roosens 1983, 162). The drawing on the right is a plan view of the castle, the line drawing presenting the described configuration without considering wall thicknesses (Roosens 1983, 157).

«The best roofs are achieved by using roof plastered with earth and trass, with stones on top. One without the other will not do».[28] Lead was a common solution for roofs, but had some disadvantages (Stevin 1650, 98–102): it was relatively expensive, it would expand considerably under warm weather, leading to gradual cracking. Also, lead would become so hot when exposed to direct sunlight, that it became almost impossible to walk there in summertime; obviously, this made the use of solid alternatives for flat roofs even more appealing. Stevin mentions in this regard that tiles, which were burnt in fire, withstand fire better than slates, lead or copper.[29] On this point, the prodigy houses of the 16th century were technically vulnerable.

Notes

ARAB RK Algemeen Rijksarchief Brussel, Rekenkamer
ARADH Algemeen Rijksarchief Den Haag
KUL AA Katholieke Universiteit Leuven, Arenberg Archief

1. The authors would like to thank Charles van den Heuvel for allowing us to consult his notes and transcriptions of Simon Stevin's texts.
2. Apparently, Beeckman met several times with the widow of Stevin in 1624, occasions upon which he had the chance to consult manuscripts and notes belonging to her late husband.
3. «Ende dese piloterijnghe sal gheschieden In dese manieren. Men sal nemen goeden Eecken houten daermen pijlen af bereeden sal, te wetene dat haeclieder langde sal wesen 10 maal naer die diepte des diameters der seluer houten, Dese pilen die sullen viercant besleghe wese ende ondere scerp, Ende soo waer keijachteghen grondt voor hande es, soo salmen aen die henden ijseren pinnen slaen, daer naer soo salmen desen pijlen wat branden, dit nu aldus ghedaen wesende, soo salmen die pilen dichte aen melckandere Inne houen ofte slaen met bijsondere Instrumenten van metaele daer toe ghemact, dese pijlen aldus Inne gheheijt wesende duer het diepste des quelms, ende al ghelijck van eender hoochde naer wijde ende breede der Edificien diemen daer oppe stellen wil, soo sal dit spatie die daer sokde mueghen wesen tussche die pilen opghevult worden met Colen, alsoc vitruuius sulce es leerende, voorts soo sullen op dese piloterijnghe ghebrocht worden goeden dicken Eecken plancke ende die ghenaegelt met goeden Coperen nagelen.» (De Beste 1599, f° 343^{v}–344^{r})
4. KUL AA 2454.
5. «Hoewel het selue soude mueghen gheschieden sonder piloterijnghen, Ende dat duer schoouijnghe, dat te nemene 3 ofte 4 steenen op melckanderen, Ende dien alsoo te sijnckene den eenen neuens den anderen, het welcke soo sekere niet gheschieden en mag, duer oorsaecke der opquelmijnghen des waters, want niet mueghelicken en es het werck aldus van eender hoochden buijten watere te brijnghene, waer duere Ick fugiere dese maniere seere onsekere. Ofte men soude dit mueghen schoouen met calck steen van een voet viercant het welcke liggende aldus Inden grondt, In hen seluen es swellende . . . ». (De Beste 1599, f° 344^{r})
6. ARADH, Grafelijkheidsrekenkamer, nr. 5008. See http://home.planet.nl/~taco.hermans/schoonhoven2.htm consulted on 24–09–2002.
7. «soo salmen daer Inne brijnghe goeden viercanten Eecken boomen ofte houte, commende voore Inde voormuere Ende oock Inde frenten (?) alsoo gherauee ende ghewrocht In melckanderen tot bijndinghe ende onderhoudinghen der muere aen melckanderen, soo dat het droomen der erden te min daere soude, dies soo sullen dese houten __ (?) wesen ende viercant besleghe este bestreken met weercken ende dinnen pecke, alsoo wij sullen scrijue In het boeck der fortificatien. Die meenijnghe van desen muehdij sien In dese figuere. In aldusdaeneghen fondamenten, soo salmen die stoffe drooghe beseghen dats sonder die brijcken nat te maekene ofte the begietene, De tijdt datmen aldusdaeneghe fondamenten beginnen sal te legghene, dat sal wesen In septembre, want dan de rehten tijdt es dat het watere cleene es, Ende oock dat de quelm dan aldermeest ghedwonghen ligt, Ende aldus soo mag dan die matselerie ligghen drooghen den gheheelen wijntere, om als dan vander eerden oppewaerts te werckene. Ock soo sal men meest vseren In aldusdaeneghe swaere wercken datmen die fondamente sal legghen In goeden harten steen kalck, duer dien dat die selue matselrie te bet soude verharden, want ist datmen kalck es beseghende van sochten steenen ofte scelpe ghebrant soo ist langhe eer dat alsulcke matselrie es drooghende . . . ». (De Beste 1599, f° 345^{r}–345^{v})
8. «Soo waer dat eeneghe dickte van mueren sijn, soo salmen vseren altijts die 5 laeghe te legghene een cruijslaeghe ofte haeijlaeghe, die welcke tot elckerder reijsen sal Contrario geleijt worden, want dit geeft een groote sterckte ende een groot verbandt In aldusdaeneghen Edificien van torren . . . ». (De Beste 1599, f° 344^{v}–345^{r})
9. «There is a species of sand which, naturally, possesses extraordinary qualities. It is found about Baiæ and the territory in the neighbourhood of Mount Vesuvius; if mixed with lime and rubble, it hardens as well under water as in ordinary buildings». (Gwilt 1826, II: 6.1)
10. «Ende ist datmen wil goede moortele hebben, soo salmen nemen watersandt daermen dat becommen can, Ende doe daer Anne poeder van ghestampten potte ofte decktegelen een derden deel, ende voorts het behoorlick kalck, Ende dit tsaemen onder ee ghemingelt ende alsoo ghemact, dat geeft een groote stercke Andewercken». (De Beste 1599, f° 337^{v}–338^{r})
11. «Ende ten desen propooste, om datmen te allen lande niet en heeft van aldusdaeneghen puluere soo sulle wij hier teghen stellen een ander maniere die men hier In desen lande onlance ghebruijck heeft, om teghe het watere te maetsene, het welcke es oock een drooghe mijne ofte stoffe, Ende wordt met naemen ghenoemt Dort steen, ofte Taraest steen, Ende wordt ghehaelt huut heete ofte drooghe gheberchten, als In hoochduijtslandt ende elders, want ontrent dese beghe ofte plaetsen daer aldusdaeneghen steen es ligghende, soo wassen die wijngaerden seere, . . . ». (De Beste 1599, f° 338r)
12. « . . . les échevins consultent Jacquemart de Saint-Ghislain de Tournai, ouvrier de pavement . . . afin qu'il

vienne à Mons et marchander de faire terrastre de thueilles moullues sur la voussure de la grosse tour, se boinement valloir pouvoit contre les eaux sans trebattre.» (Pierard 1981, 351)

13. «Tarrast versteent wel int water alst niet geduerich door en loopt, in ses weken; buijten t'water in veerthien dagen». Beeckman, I. Journael. f° 226^{v}, lines 1–2 (De Waard 1942).
14. «Om kelders in tarrast te leggen, men leght eerst sandt daerna een bedde van calck, daerop legt men dropsteen in tarras, seven steenen hoogh, ende ondertusschen viermael overal met tarrast». Beeckman, I. Journael. f° 226^{v} (De Waard 1942).
15. „Om te stoppen een splete in tarrast, daer water door compt, men sal nemen een deel roomenij, dat mael sooveel ongeblust, ende cappelingh van botermelck, dat men van boven met een lepel van de melck sal scheppen, alse begint te sien, ende maken daeraf een pap». Beeckman, I. Journael. f° 226^{v}, lines 24–28 (De Waard 1942).
16. Used for Salomon de Caus's first grotto fountain in the ducal palace at Brussels (1603). ARAB RK 27504, Oct. 1-Dec. 31, 1603, f° 64^{r}: «A Pierre Vastelavondt [sic] et Henry Cortvrindt la somme de . . . a quoy porte certaine quantite de laict et de formaiges par eulx desbourse et livre a diverses fois durant le terme . . . pour la confection du ciment, servant pour attacher les cochilles et aultres ornemens a la roche de lad(ite) fontaine artificielle . . . »; ibid., f° 64^{r}; 27305, 1604–1605, f° 24^{v}.
17. «De tweede wijs is onlancx t'Amsterdam int gebruyck gerocht alwaer seer leech lant zijnde, maken het deel onder water commende, van hout stoppen dat met mos en teer, en onderhoudent gelijckmen de schepen doet». A similar remark is included in Isaac Beeckman's Journal, f° 231^{r}, lines 1–3 (De Waard 1942).
18. ARAB RK 27306, part II, 2nd acount, f° 445^{v}, 446^{r}, 446^{v}, 447^{v}, 606^{r}, 607^{v}.
19. ARAB RK 27306, part II, 2nd account, f° 554^{v}–555^{r}, 555^{v}, 557^{r}–558^{v}, 560^{r-v}, 705^{r-v}.
20. In particular Madrid, Museo del Prado, inv. n° 1434 (view from the south-west, 1611–1612) ; Dijon, Musée des Beaux-Arts, inv. n° CA102 (view from the south, 1612) ; and Munich, Alte Pinakothek, inv. n° 1893 (view from the north-west, 1611). (Ertz 1987, 157–163)
21. ARAB RK 27307, f° 123^{v}–124^{r}, 130^{r}: «clef dargille».
22. ARAB RK 27306, part II, 2nd account, f°614^{v}: « . . . avoir fait et mis en oeuvre aux sourplanchiers dud(it) hostel de Mariemont le nombre de ij^{C}xij beneaux dargilles»; f° 615^{r}: « . . . avoir fait et mis en oeuvre sur les thourettes et porte dud(it) hostel le mortier de seize beneaux dargilles . . . ».
23. « . . . ende dat verwelfsel vander gaelderye zal liggen in tarras ende daer zalmen up gaen ront omme in elck vande voornoemden cameren om mijnen here te dienen, . . . » taken from Raeminge vant maecken vanden huijse oft slote van Diest, tempore comitis Henrici de Nassau. ARADH, Nassausche Domeinraad, 1st section, nr. 1076, f° 4^{v}, paragraph 19 (Roosens 1983).
24. « . . . mids dese derde verdiepijnghe datse zal zijn verwolven ende gheleyt in tyras, ende daer en zal gheen dack boven zijn, ende men zal den vloer int upperste paveren oock met tarras, . . . ». Raeminge vant maecken vanden huijse oft slote van Diest, tempore comitis Henrici de Nassau. ARADH, Nassausche Domeinraad, 1st section, nr. 1076, f° 3^{r}, paragraph 15 (Roosens 1983).
25. Raeminge vant maecken vanden huijse oft slote van Diest, tempore comitis Henrici de Nassau. ARADH, Nassausche Domeinraad, 1st section, nr. 1076, f° 4^{v}, paragraph 22 (Roosens 1983).
26. Taken from the Records of the building of Longleat, II, 121 (Girouard 1983).
27. Raeminge vant maecken vanden huijse oft slote van Diest, tempore comitis Henrici de Nassau. ARADH, Nassausche Domeinraad, 1st section, nr. 1076, f° 4^{v}, paragraph 20 (Roosens 1983).
28. «Besten daken loof met potaerde ende tras, en steen daerop. Elck bysonder en is niet goet.» Beeckman, I. Journael. f° 227^{v} (De Waard 1942).
29. « . . . tegelen . . . welcke int vier gebacken zijnde, den brant connen verdragen beter dan leyen, loot of coper.» (Stevin 1650, 118–119).

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The methods of graphical statics and their relation to the structural form

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In the preface of the 2nd edition of his main work «Die graphische Statik» (1875), Karl Culmann was pleased to report that graphical statics had been taken up widely, but at the same time he complained that it was taught without the mathematical base of the projective geometry. Subsequently, the «Graphostatik» (graphostatics), characterised by its recipe-like structure, became generally accepted.

The graphostatics formed an essential means of intellectual engineering practice. It still referred to the unity of design, calculation and construction. Various examples demonstrate the option of deriving from the graphical examination not only the internal forces required for dimensioning, but also criteria for optimising the structural form. Nevertheless, with the completion of the classic structural theory after 1890, the decline of the graphical statics in favour of analytical calculation methods was already becoming apparent. This corresponded with the desire to rationalise the engineer's work, but it led to the disintegration of the unity of design, calculation and construction.

Today unlike in engineering practice, graphical methods still play an important role in lecturing on structures. The clarity of graphical techniques has a high didactic value, since interdependencies, e.g. between forces and structural geometry, can be directly experienced visually. Architecture and structural engineering students thus are provided with a suitable means of evaluating not least historic structures. Recent examples from engineering practice demonstrate how helpful the know-ledge and use of graphical methods can be for the evaluation and preservation of historic structures: The history of structural methods is therefore an important facet of construction history.

Graphical statics and graphostatics in the work of Culmann

Graphical statics started with the publication of the monograph under the same title between 1864 and 1866. Karl Culmann (1821–1881) had been lecturing graphical statics at Zurich Polytechnic (now known as ETH) since 1860 (Maurer 1998). According to its creator, it is an attempt «to solve engineering tasks that are accessible to geometric treatment with the aid of the new geometry» (Culmann 1864/1866, VI). With «new geometry», Culmann refers to the projective geometry going back to the publication by Jean Victor Poncelets (1788–1867) entitled «Traité des propriétés projectives des figures» (Poncelet 1822), investigating the projective characteristics of figures. How does this projective geometry, which is after all freed from metrics, i.e. from dimensions and numbers, and which is only interested in the relative position of geometric figures, relate to graphical statics, with the latter dealing specifically with the measuring of geometric parameters?

The answer is provided by means of an example, based on Culmann's mathematical proof of the projective relationship between funicular polygon and force polygon, which had already been introduced by Pierre Varignon (1654–1722) (Figure 1).

For the special case of an equilibrium system of forces with one point of application, Culmann found the «structural relation between funicular polygon and force polygon via a planar correlation of the projective geometry» (Scholz 1989, 174). Funicular polygon and force polygon are interchangeable in so far as it does not matter which of the polygons is regarded as the system of the lines of action in addition to the associated funicular polygon. Culmann describes such figures as reciprocal (Figure 2).

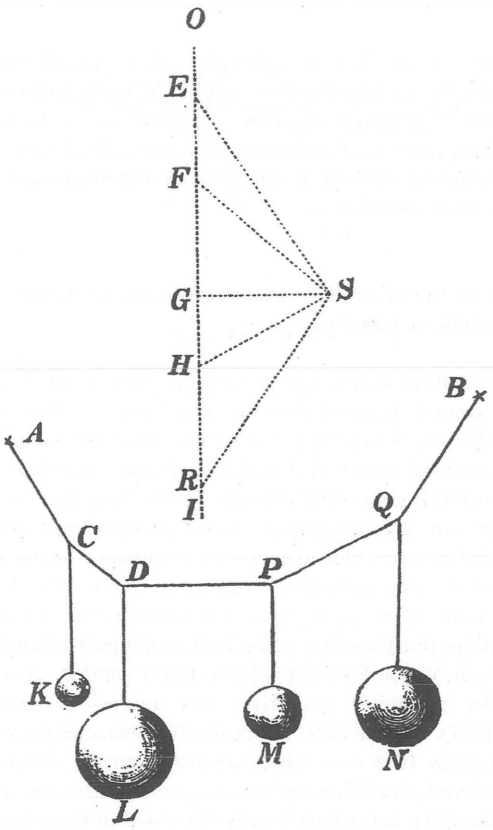


Figure 1
Funicular polygon and force polygon according to Varignon. (Varignon 1725)

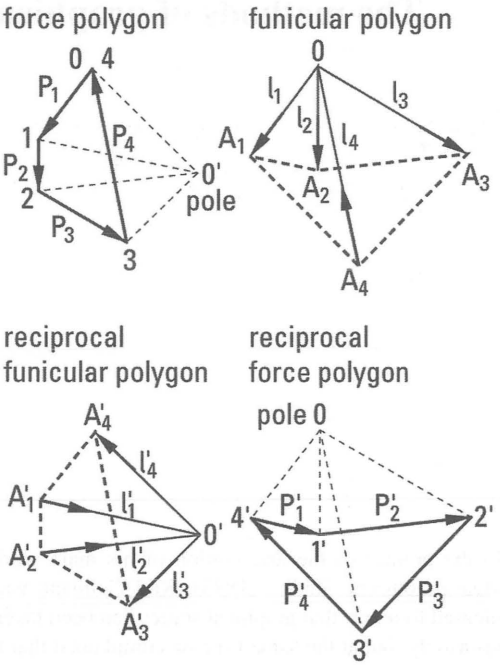


Figure 2
Reciprocal diagrams of funicular polygons and force polygons for plane systems of forces according to Culmann. (Kurrer 2002, 224)

Soon after the publication of Culmann's «Graphische Statik», graphical statics became separated from its applications in the form of graphostatics. Evidence for this can be found in the even more mathematically oriented second edition published in 1875, in which Culmann promises the reader to elaborate on the applications in a second volume (Culmann 1875, XIV). However, this never happened, because Culmann's scientific thinking was too much determined by the ideal of an axiomatic substantiation of graphical statics.

Culmann's visualisation of beam statics via the funicular polygon (Figure 3), which is an important component of graphostatics, is dominated by the operational side that is restrained in the means/purpose relation. Relying on measures and numbers, it rationalises and mechanises an important side of the working process of the engineer through informational consolidation in the form of graphical

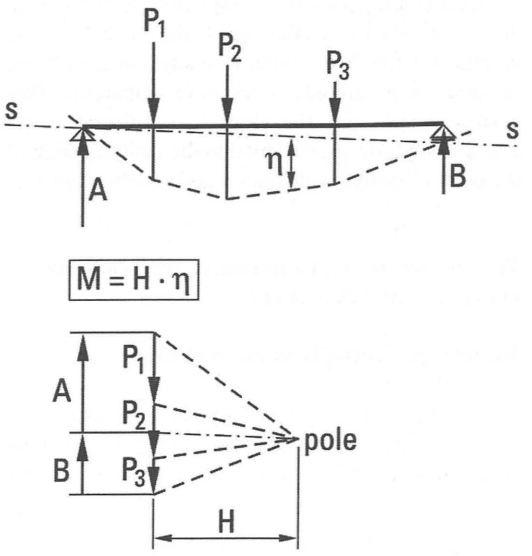
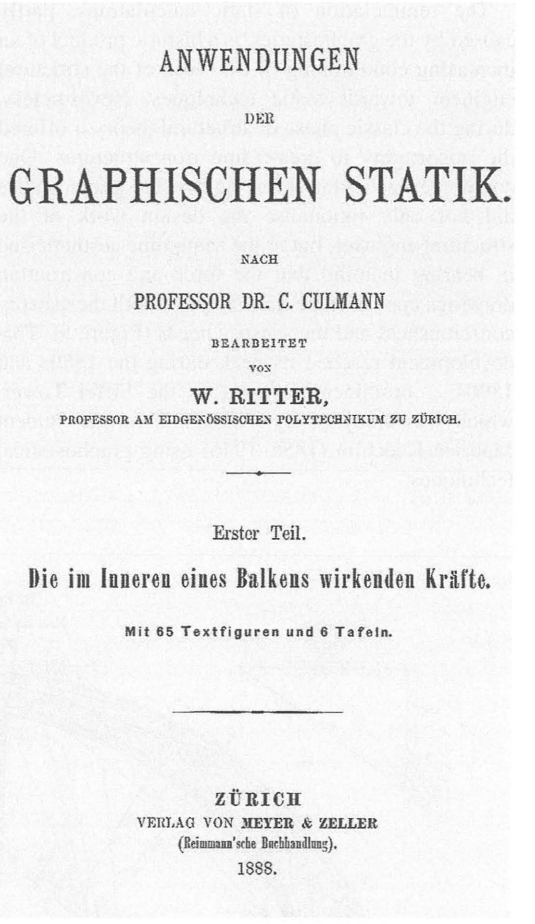


Figure 3
Graphical solution representing the bending moment diagram of a simply supported beam according to Culmann. (Kurrer 2002, 224)


ANWENDUNGEN

DER

GRAPHISCHEN STATIK.

NACH

PROFESSOR DR. C. CULMANN

BEARBEITET

VON

W. RITTER,

PROFESSOR AM EIDGENÖSSISCHEN POLYTECHNIKUM ZU ZÜRICH.

Erster Teil.

Die im Inneren eines Balkens wirkenden Kräfte.

Mit 65 Textfiguren und 6 Tafeln.

ZÜRICH

VERLAG VON MEYER & ZELLER

(Reimmann'sche Buchhandlung).

1888.

Figure 4
Title page of Ritter's «Anwendungen der graphischen Statik». (Ritter 1888)

methods. Graphostatics mediates between the manpower of the engineer and his object, here in the form of ideal static models. Graphostatics represents an important intellectual tool of the engineer, which had its heyday in the last third of the 19th century within the structure of fundamental engineering sciences and structural engineering.

While graphical statics was the keystone of the establishment phase of the structural theory that had started with the trussed framework theory (1850–1875), the emancipation of graphostatics from graphical statics and its cognitive expansion was an important moment in the completion phase of the structural theory (1875–1900). Even Culmann's student and successor at ETH Zurich, Wilhelm Ritter (1847–1906), became disloyal to graphical statics and his own view of its basis on projective geometry, as it was formulated in the foreword of his four-volume work published between 1888 and 1906 «Anwendungen der graphischen Statik. Nach Professor Dr. C. Culmann», Figure 4: He wrote a work on graphostatics, in which this view only appeared in the form of a mere «manner of speaking» (Scholz 1989).

In 1882, Ludwig Tetmajer (1850–1905) recognised the influence of Culmann's graphostatics as follows: «The grand bridge arches that were constructed in Switzerland since 1876 have all been calculated according to Culmann's theory, with contributions from construction enterprises such as Holzmann and Benkieser in Frankfurt, Eiffel in Paris, (. . .) in order to be able to utilise the results of Culmann's research in their construction bureaus.» (quoted after Stüssi 1951, 2).

The renunciation of static calculations, partly caused by the graphostatics, is a historic product of an increasing conditioning of the work of the structural engineer towards static techniques. Nevertheless, during the classic phase of structural theory it offered the opportunity to create fine iron structures. One could even go as far as saying that the graphostatics did not only rationalise the design work of the structural engineer, but at the same time aestheticised it, bearing in mind that the force and construction drawings appear in the dual shape of both the sensory consciousness and the sensory needs (Figure 5). This development reached its peak during the 1880s and 1890s; a prominent example is the Eiffel Tower, which was analysed by Culmann's former student Maurice Koechlin (1856–1946) using graphostatical techniques.

Nevertheless, with the completion of the classic theory of structures after 1890, the decline of the graphical methods in favour of analytical calculation methods was already becoming apparent. This corresponded with the desire to rationalise the engineering process, but it led to the disintegration of the unity of design, calculation and construction.

The significance of graphical methods for lecturing on structures

Visual experientiality of interrelations

Whilst in modern engineering practice, graphostatics is largely seen as a historic variety of structural analysis, its techniques are still relevant in lecturing

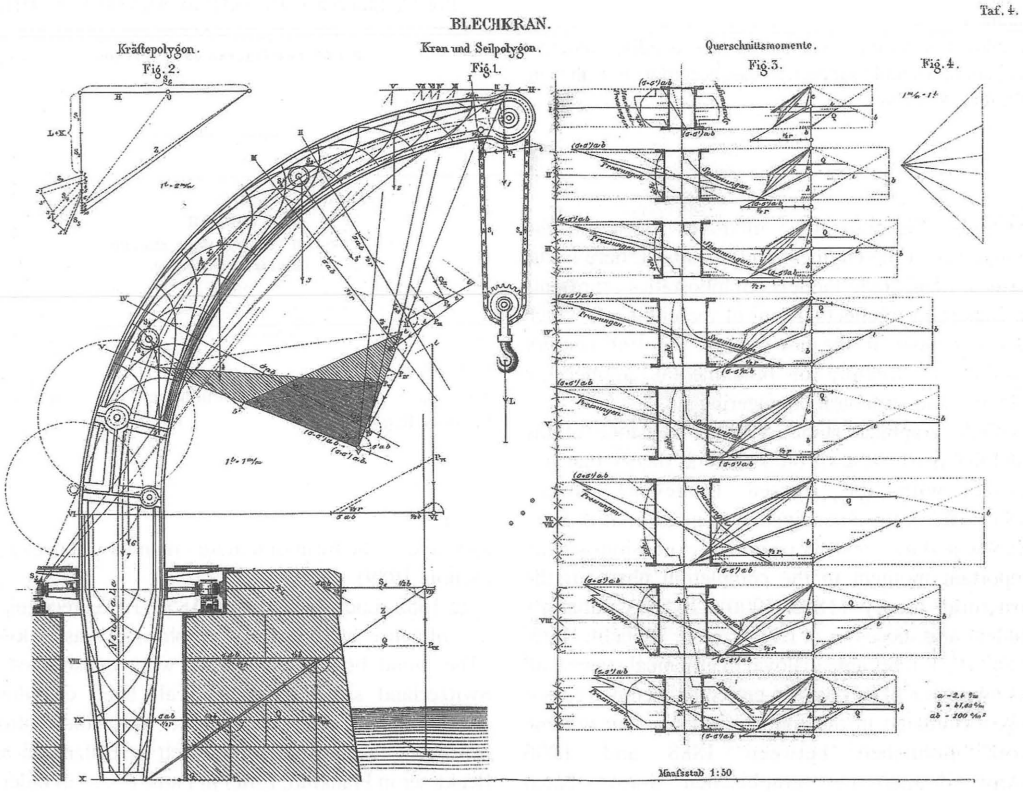


Figure 5
Graphical solution of a metal crane according to Ritter. (Ritter 1888)

on structures. The clarity of the graphical method has a high didactic value, since interrelations and interdependencies, e.g. between structural geometry and forces, can be directly experienced visually.

The Cremona diagram shown in Figure 6, for example, clearly illustrates how a reduction of the forces acting in the members of a framework can be achieved by increasing the depth of the trussed girder under consideration.

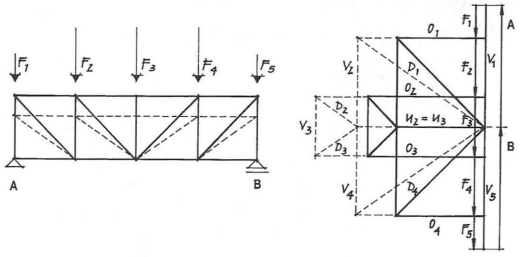


Figure 6
Cremona's diagram of forces for a trussed girder. Comparison of two girders with different depths.

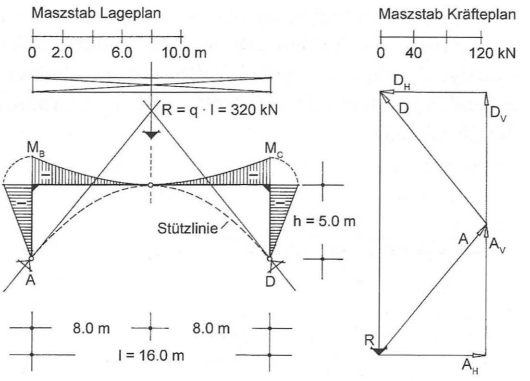


Figure 7
Symmetrical frame with three hinges. Graphical determination of the supporting forces by means of the thrust line. (Gerhardt 2002a, 65)

Optimisation of the structural design

Design, dimensioning and construction and their mutual influences can be experienced as a unit in graphical solutions. Criteria for the optimisation of the structural form are almost imposing themselves: The optimisation options are directly apparent and can be implemented directly in the design without the need for complicated calculations.

An example is the three-hinged frame shown in Figure 7. Based on the theory of the thrust line, the supporting forces can easily be determined, and therefore also the bending moments at critical points (corner joints). The graphical optimisation shown in Figure 8 leads to a more balanced distribution of bending moments with significantly reduced maximum values by relocating the hinge. The interrelation between hinge relocation, thrust line and reduction of horizontal reaction forces can clearly be seen in the graphical solution.

For lecturing on the theory of structures it has proven useful to extend the application of graphical

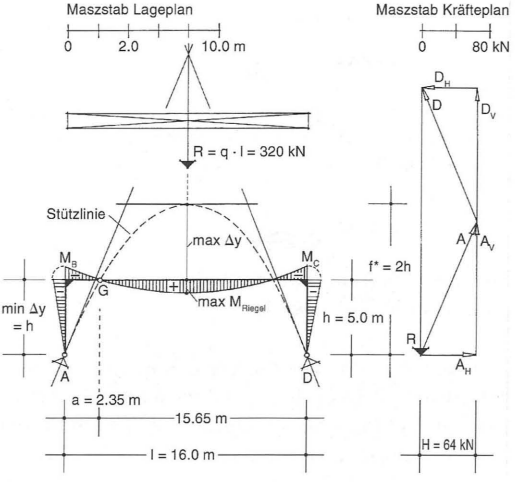


Figure 8
Frame with three hinges. Graphical optimisation of the position of a hinge in order to minimise the bending moments. (Gerhardt 2002a, 69)

solution techniques to statically indeterminate systems, as far as possible with simple procedures. The principle of the thrust line can thus also be used, for example, for examining statically indeterminate frames, Figure 9, by assuming realistic ratios of beam

stiffness to post stiffness. The zone in which all 'reasonable' bending moment curves and thrust lines respectively are located can thus be defined quite exactly, despite the statical indeterminacy (Führer, Ingendaaij, Stein [1984] 1995, 201–6; Gerhardt 2002b, 381–3).

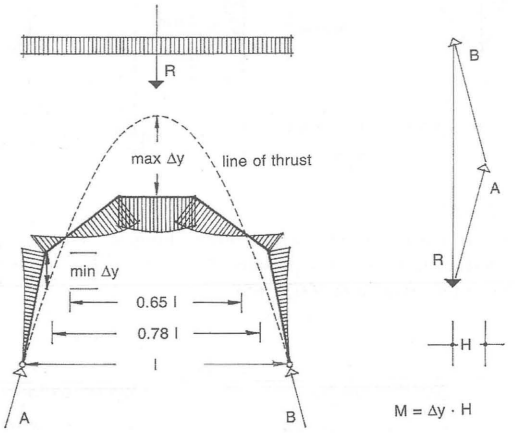


Figure 9
Bending moment diagram of a frame with two hinges. Optimised structural form as it approaches the line of thrust. (Gerhardt 2002b, 383)

«The aim of this procedure is to make the relationship between structural form, external load and the resulting bending moments directly experienceable through experiments with hanging chains.» (Gerhardt 2002a, 8)

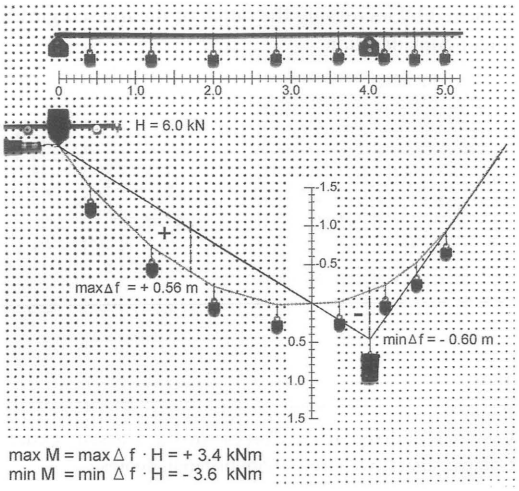


Figure 10
Overhanging beam. Experimentally derived funicular polygon representing the bending moment 'diagram'.(Gerhardt 1998, 35)

The use of demonstration models in lecturing on graphostatics

Experiments with demonstration models have proven didactically helpful for communicating theoretical facts in lecturing on structures. Studies show that theories are easily understood and lastingly memorised by students due to the illustrative quality of model experiments (Faisst 1975).

The graphical method of determining bending moments via force polygon and funicular polygon can also easily be experimentally demonstrated with hanging chains. Here, the behaviour of a hanging chain under load, which resembles the bending moment curve of a beam under the same load, is utilised. The representation of the bending moment diagram via hanging chains as shown in Figure 10 is the materialisation of the graphical funicular polygon.

«For the dimensioning of structural components, the magnitude and distribution of bending moments are a basic criterion and are often crucial. Whilst the internal moments acting in a structural element subject to bending stress are often difficult to imagine, it is much easier to do so for the deformation of a hanging chain under an equivalent load. Via the analogy of the catenary, the qualitative shape of the bending moment curve is thus directly comprehensible. The method of experimental representation of bending moments can thus contribute to the safe estimation of bending stresses independent of calculations, and to the optimisation of load-bearing structures even during the design phase.» (Gerhardt 2002a, 8)

Distribution of forces and structural form

The correspondence of structural form and physical stress inevitably implies both structural and formal aesthetic qualities (Figure 11).

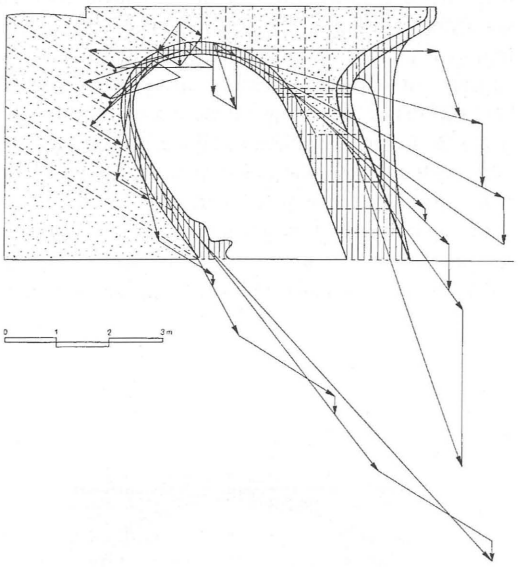


Figure 11
Park Gúell (1900–1914). Retaining wall towards Muntanya Pelada. The diagram of forces demonstrates the way Gaudí was determining the most effective shape of retaining walls. (Sweeney and Sert 1960, 74)

Load-bearing structures or structural elements that are shaped according to the flow of forces are convincing not only due to their consistency regarding the transfer of loads, but in addition they possess an aesthetic harmony that can positively shape the whole architectural appearance of a building. In view of the formal randomness of shape that prevails in the design of many buildings, even in times of high-tech architecture, the training of both architects and structural engineers has to communicate the capability to derive a sensible design from the function of load transfer. The graphical methods have a special significance in achieving this aim, since they visualise the distribution of forces in the examined structural elements in an excellent way and thus are able to have a positive influence on the design process for load-bearing structures, in the sense of the unity of design, calculation and construction mentioned above.

Analysis of historic structures

One of the tasks of lecturing on structures is the critical examination of historic constructions. Through the graphostatical techniques, students become acquainted with an appropriate tool for analysing, evaluating and preserving historic supporting structures.

Suspended models based on the theory of the thrust line are particularly useful for the analysis of historic vault or arch structures. This gives architecture and structural engineering students the opportunity to examine for example the loadbearing behaviour of masonry domes, without having to acquire deep knowledge of the complex and abstract mathematical techniques of structural vault analysis. However, such an approach is inconceivable without any knowledge of graphostatics and the graphical techniques of representing forces as vectors.

Figure 12 shows a suspended model produced by architecture students at Aachen University for analysing the distribution of forces within the cupola of the cathedral at Aachen (S. Seyedahmadi and T. Daniel. Lehrstuhl für Baugeschichte und Denkmalpflege und Lehrstuhl für Baukonstruktion (Tragwerklehre). Tutors: B. Schindler, R. Gerhardt). The three-dimensional suspended model gave an insight into the annular tension forces acting within the wrought-iron ties inserted into the basis of the vaulted masonry construction. The model also enabled statements to be made about the weight of the stones in the upper zone of the cupola.

Recent applications of graphical methods in engineering practice

With examples from engineering practice, the consulting engineer's office 'Pichler Ingenieure', with contributions by Karen Eisenloffel and Marko Ludwig, demonstrates how graphostatics as a «language of the engineer» (Culmann 1875, 5) can be

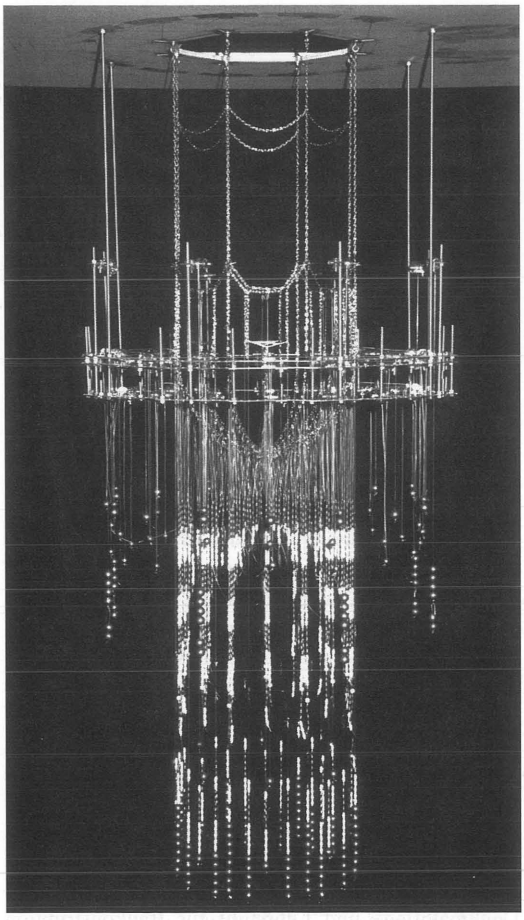


Figure 12
Three dimensional suspended model to analyse the flow of forces in the cupola of the cathedral at Aachen. (Seyedahmadi und Daniel 2002)

utilised even today with the aid of the computer (Pichler et al. 1998). A particularly good example of this approach is the statical examination of the large-span ribbed vault above the main staircase of the city hall «Rotes Rathaus» in Berlin (Figure 13). Cracks had appeared in the plastered brickwork of the ribbed vault, the reasons for which had to be found. The intention was to turn the space above the ribbed vault into a banqueting hall: «We had to investigate whether the damage may have been caused by an overload of the vaults and whether the structure could withstand the envisaged load increase. Due to the type of damage, a steel girder grid to relieve the vault had been considered initially» (Pichler et al. 1998, 227). It appeared sensible to use graphostatics to check anew whether the existing construction would be able to withstand the expected loads. «The force diagrams and thrust lines of the graphical solution were drawn using CAD, so that the iteration steps required for the branched ribbed vault could be carried out without excessive effort and could be checked using a drawing of the existing vault. The result of the first calculations taking into account the additional live load was not surprising. For unilateral loads, the thrust line was outside the vault, i.e. the vault would fail. The advantage of the graphical method —in contrast to spatial computer calculations— is that it indicates a solution through

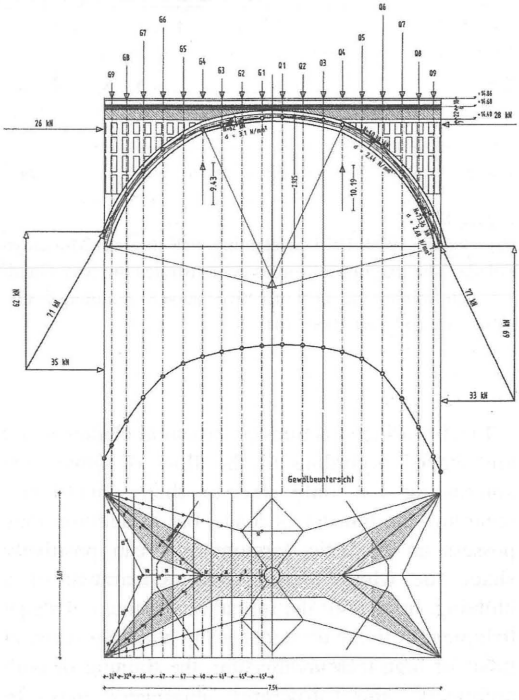


Figure 13
Computer-aided graphostatical investigation of the cross-vault spanning the foyer of the Berlin city hall «Rotes Rathaus». (Eisenloffel and Ermer 2000, 85)

its clarity, namely that increasing the dead loads would prevent the thrust line from leaving the vault. With a ballasting sand layer of 20 cm thickness above the vault, the course of the thrust line could be influenced in such a way that, for a unilateral live load of 3.5 kN/m≈ with a maximum compressive strain of 1.5 N/mm≈, the vault could be shown to be safe.» (Eisenloffel and Ermer 2000, 84–6)

The initially envisaged additional support grid thus became superfluous.

The combination of graphostatics and CAD not only enables the examination of vector and shape-active structures, but also mass-active structures such as floor slabs (Pichler et al. 1998, 229).

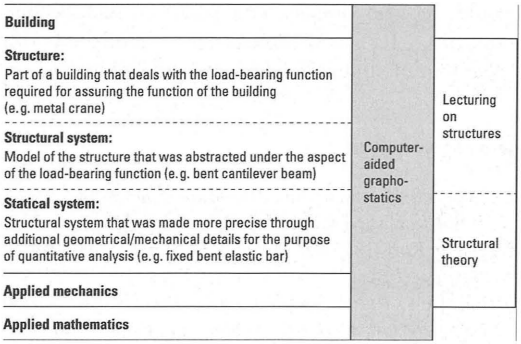


Figure 14
Subject and position of computer-aided graphostatics. (Kurrer 1998, 209)

Outlook

The increasing rationalisation of the engineer's work during the completion phase of the theory of structures (1875–1900) soon lead to the disintegration of graphical statics into respective individual methods, i.e. graphostatics, representing merely graphical recipes. In a development that is comparable with the later introduction of computer statics, graphostatics made structural engineers move away from the design process in so far as graphostatical recipes became a mere means of intellectual techniques, i.e. a technical means or 'techne'. The aesthetic component also faded from the design work of structural engineers. Computer statics reinforced the tendency towards structural design based purely on analytical calculation.

Nevertheless, modern information and communication technology already points towards a systemic design practice that enables structural engineers to regain lost design competency and enables architects to regain lost structural competency on a higher level. One option for moving away from structural design purely based on analytical calculation is the creation of computer-aided graphostatics, positioned at the interface between the practice of structural engineers and of architects in the theory of structures (Figure 14).

Computer-aided graphostatics would have to be designed modularly, so that the user would be able to mobilise each individual structure, e.g. the funicular polygon, through specially developed graphics editors, display it on the screen and combine it with other graphics editors into concrete structures in the sense of graphostatics. Such graphics editors and dimensioning modules based on approximation methods could enable the results of the graphostatical synthesis to be transferred directly to the level of the structural system. Computer-aided graphostatics would thus become the hinge between design and construction. Not least it would be a suitable didactic means to bring together structural engineering and architecture students in the theory of structures.

Further elements could be deduced from the kinematic structural theory developed in the 1880s (Kurrer 2000, 44). For example, the graphical techniques derived from the influence line theory created by Otto Mohr (1835–1918), Emil Winkler (1835–1888), Johann Jakob Weyrauch (1845–1917), Heinrich Müller-Breslau (1851–1925) and in particular Robert Land (1857–1899) during the 1870s and 1880s would provide an appropriate representation for adapted graphics software. Land's theorem would be a nice example for the rediscovery of the visualisation of statics; its graphic re-presentation through the symbolic machine of the computer could significantly increase the 'statical feeling' of the user for the influence of moving effects on the force and displacement parameters.

Computer-aided graphostatics could make the aesthetic component in design work become reality again, since it would facilitate the lost 'statical feeling' at the interface of design and construction becoming second nature again to the user: science

would become sensory and poetry would become scientific. It could break the established role behaviour of structural engineers and architects.

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Drawing, reasoning and prejudice in Choisy's Histoire de l'Architecture

Fco. Javier Girón Sierra

Choisy's «Historie de l'architecture», is considered a landmark in architecture historiography addressed from the point of view of constructive rationalism.[1] In this paper, we intend to examine:

— What are the kinds of historical «processes» considered by Choisy as those that make up the history of architecture.
— What are the diversity of graphical procedures used by him and what is their role in the elaboration, exhibition and analysis of those procedures.
— Lastly, what kind of relationship does he establish between these aspects and other disciplines, particularly natural science.

In order to answer these questions, we shall start by examining his «graphical discourse» and take it as the basis for other considerations.[2]

In Choisy's History, does exist a variety of graphical approximations, which define a parallel speech to that outlined in the text. Some peculiarities of his drawings are noticeable, especially his use of axonometric from below or his particular way of making a building's anatomy, but there are many others that have remained fairly unnoticed. A first intriguing feature is the frequent use of «evolutionary drawings», especially in Grecian and Gothic architecture study. If, as we shall do here, we isolate them from the text itself and put them together, this fact becomes even more obvious and somehow bring memories of drawings showing evolutionary scales that have been used sometimes in natural history. The use of cartographic representations is another aspect that, anecdotic as it may seem, was not ordinary.

What lies behind those graphical discourses? And, confronted with others, how valuable are they?

Progressive drawing and naturalistic analogies in Choisy

Precedents and formation of progressive drawing

In the 40' of XIX century, we find a background for «evolutionary» drawing: the studies of synoptic charts proposed by A. de Caumont (1841), Batissier (1845) and Daly (1845–6). These are graphical representations of buildings' fragments showed in a chronological sequence, although their authors do not become aware of a progressive and connected evolution.

An interesting feature appearing in these synoptic charts is that different periods are expressed by a language close to that used in geology and palaeontology, for instance there are «transitional» Romanic capitals and «primary ogival», «secondary» and «tertiary». These terms, coined by Caumont and Batissier and still used by Tubeuf, could suggest the possibility of building a history of architecture similar to that of geology.

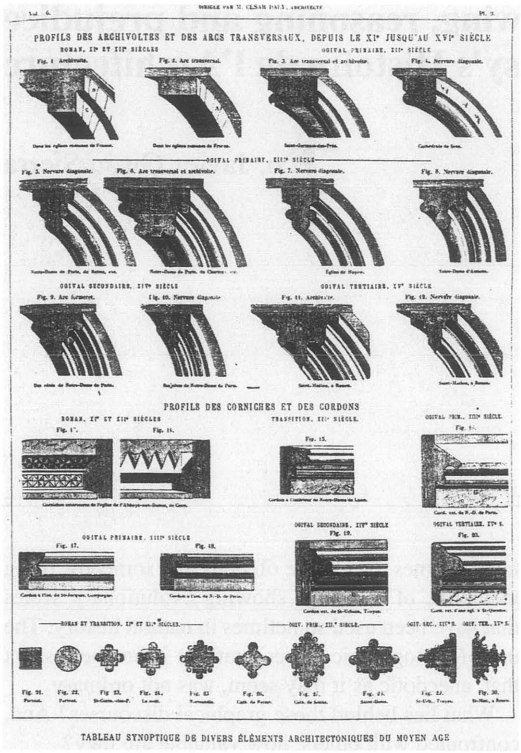


Figure 1
A comparative display of architectural fragments («tableau synoptique») by Batissier published in the «Revue Générale»

Some years later, Viollet-le-Duc will criticise this kind of classification, as it shows a discontinuous historical process. In the first volume of its Dictionnaire Raisonné, first preface (1875, p. V), he accepts that incipient studies on the Middle Age divided the art of that period «par styles *primaire, secondaire, tertiaire,* de *transition»,* and assumes «que la civilisation moderne avait procédé comme notre globe, dont la croûte aurait changé de nature après chaque grande convulsion» . . . But this ages approach —with revolutions and crisis— does not adjust to the continuous model that he believes it corresponds to Gothic.

According to Viollet-le-Duc, continuity in natural history was better reflected by another model —comparative anatomy. As we can read in his article «Profil» (522–23), what happens «en décomposant un edifice du XV siècle» is that one can see, once developed, what it was only the germ of an idea in the XII century, and that:

> en présentant une suite de'examples choisis entre ces deux époques extremes, on ne saurait, en aucun point marquer une interruption. De même, dans l'ordre de la création, l'anatomie comparée présente, dans la succession des êtres organisés, une échelle dont les degrées sont à peine sensibles, et qui nous conduit, sans sobresauts, du reptile à l'homme.

Some of the drawings in this article show how Viollet-le-Duc understands this gradual process, progressive, by its details.[3] It must be said that this «échelle» has more conceptual affinity with the archaic versions of it (as, for example, would be represented by Charles White's drawings in his «regular gradation of men») than with the evolutionary sequences of Darwinists such as Huxley.

In Choisy's History, graphical examples will be even more abundant and systematic, both in Grecian and Gothic architecture.

As an example, there is the gradual transformation of the «organe d'appui, la pile gothique» (II, 294–5). It also draws attention to how each detail of the pillar and the ribs undergo this process. Drawings show how «se succèdent et s'enchaînent les transformations progressives du membre élémentaire de la nervure» (II, 344–6). Such modifications «se rattachent par une transition sans lacunes à celles des meilleures époques». He also arranges in sequences the evolution from the cylindrical pillar to the rib pillar, until finally a sort of exhaustion is provoked and a return to the original point happens: «alors la complication devient extreme . . . on revienne à l'appareil primitif . . . »(II, 348–51). This transition is followed by the loss of the capital, that will evolve into two varieties (II, 353) and that Choisy will want to look at, as he considers it an «atrophy» processs (II, 354) (drawings have been rearranged in the time sequence described in the text, in order to visualize this successive transformation in a better way).[4]

To a great extent, these drawings are based in Viollet-le-Duc's theories about Gothic style. But, there is something new in Choisy. Grecian architecture also exhibits graphically its evolutionary nature. In this respect, we can see how the passing of time has introduced subtle changes in Doric order

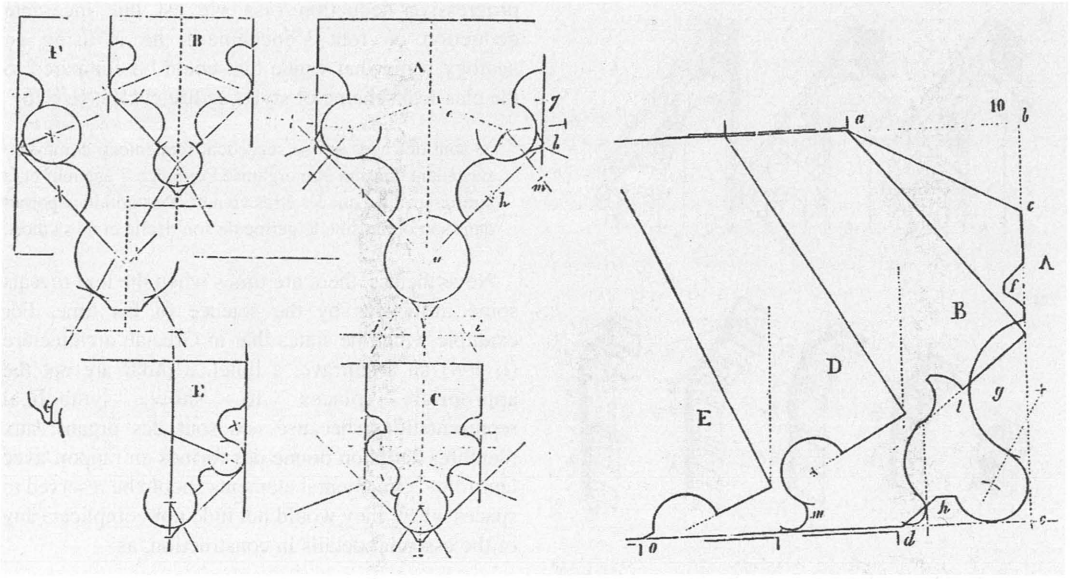


Figure 2
Reasoning as Nature does: A sequence of gothic profiles as proposed by Viollet-le-Duc

details: that is the case with the capital (I, 315–6), which, from a point of view of strength and load support, would respond to a «sentiment instinctif des formes» (I, 316). There was also a gradual increase in the arquitrave span that had previously diminished, when stone substituted wood (I, 318–9). Similarly, the pillars in antis of temples adopted gradually the most perfect form (I, 328–9).

Of all graphics, the most interesting is the one in which (I, 302), in a coherent constructive way, we can see how the Doric order shapes progressively in stone what at first was only an imitation of a procedure in

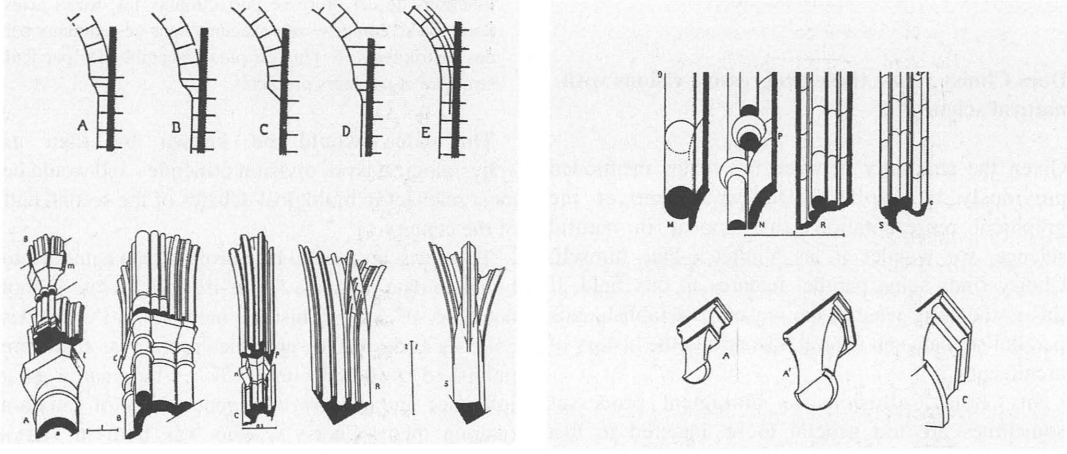


Figure 3
Some of the drawings used to reveal a progressive transformation of a gothic pile in Choisy's «Histoire»

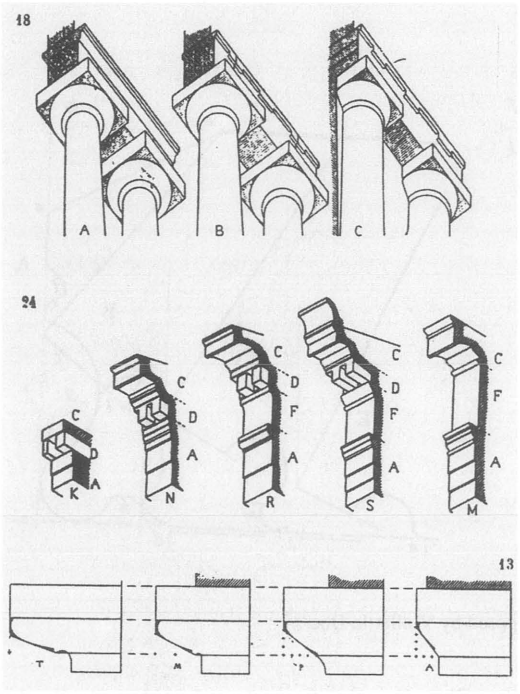


Figure 4
Reason and deduction at work. Some examples of progressive rational improvements in ancient Greek architecture

wood. We shall go into how important this is later. Now, let's focus on a different aspect.

Does Choisy relate these progressive visions with natural science?

Given the similarity between the scales mentioned previously by Viollet-le-Duc and some of the graphical representations that appear in natural science, we wonder if, as Viollet-le-Duc himself, Choisy finds some parallel features in this field. If this is the case, what is the reason to establish such parallelism between natural history and the history of architecture?

In Choisy, allusions to biological processes sometimes are too general to be inspired in that moment's science. When he states that continuity of Gothic solutions derives from a logical process of progressive deduction («sa vie est une incesante deduction où tout s'enchaîne»), he is using an analogy somewhat vague that could be compared to the classical scheme of styles as life cycles (II, 526):

> ce sont des ages qui se succèdent fatalement, comme se succèdent dans un être organisé l'enfance, l'âge mur et la vieillesse: ainsi que les êtres vivants, l'art gothique portait dans son organisme le germe de son declin et de sa mort.

Nevertheless, there are times when the text reveals some influences by the science of his time. For example, when he states that in Grecian architecture (I, 294) an arquitrave, a lintel, a pillar are not the appropriate places to show symbolical representations, because «ce sont des organs: aux membres actifs on donne des formes en rapport avec leur rôle». Ornamental elements should be reserved to spaces where they would not hide nor complicate any of the essential details in construction, as:

> Un signe de supériorité chez les êtres vivants reside dans la division des fonctions; de même pour l'art grec, à mesure qu'on approche de la perfection, les fonctions se localisent.

This sentence evokes what Henry Milne-Edwards had said in 1827 for the first time:

> Si nous examinons les organes destinés à la vie de relation, nous verrons qu'ils suivent la même loi de complexification croissante de l'organisation et de division du travail . . . et qu'à mesure qu'une des fonctions de cet ordre se perfectionne, les divers actes dont elle se compose son exécutés dans ces animaux par des instruments de plus en plus diseemblables par leur structure et par leurs propietés.

This idea would be known by then as «physiological work division principle» and would be most relevant in biological debates of the second half of the century.

There was no need to be a professional naturalist to be up to date, because Milne-Edwards wrote school books as «Cahiers d'histoire naturelle, à l'usage des colleges et des écoles normales primaires» that were published from 1833 until 1877, which had a great influence in at least two generations of children (among them, Choisy's, who was born in 1841). Spencer (1877), who was read widely at the time, also could have an influence, as he developed the

transformation from homogeneous to heterogeneous principle and its relationship with arts and architecture (. . . 27–33).[5]

Why this kind of drawing should be restricted to Grecian and Gothic architecture?

In its «Profil» article, Viollet-le-Duc gives us a clue to understand why Choisy will only create those «evolutionary» drawings just for Grecian and Gothic architecture. Only these can be defined as art, «c'est à dire, que nous la considérons comme une véritable création, non comme un accident».

So, according to Choisy and Viollet-le-Duc, Gothic architecture is a continuous logical process of progressive improvement and refining. Such a process reminds the work of nature when designing species. Men do their best in order to achieve the best possible architecture: in their own way, men are involved in an analogous genuine creative process.

Choisy's outstanding approach will consist in studying Grecian architecture from this point of view with a much clearer determination than that of Viollet-le-Duc. For a rationalist, the obstacle in Grecian architecture is that it seems to start from an illogical idea: imitating in stone a wooden architecture. If this is true, we cannot speak of a chained logic, of a «rational» and «natural» simultaneous evolution. In fact, Viollet-le-Duc is compelled to explain that there was no such imitation, but a creation in stone from the beginning. Although this was a clever explanation, Choisy must have thought it was a bit too forced. Being honest, he must have admitted that the Greek had sinned when copying in stone a previous solution made of wood. How to state then that there was a rational and gradual evolution?[6]

It is worth looking at the drawing on page I, 302. What does it tell us? It shows how what initially was an incorrect imitation of a wooden construction, in fact ends up making sense, step by step. The subtlety of the Greek, their superiority and their ability to evolve lies in having posed the problem of transforming imitation into a constructive architecture. For Choisy, this «petrification» phenomenon has its alibi in nature «Autant vaut reconnaître ici un de ces phénomènes de permanence si fréquents dans l'histoire du langage et de la vie organique elle même: un type qui survit aux functions qui l'ont originairement justifié» (I, 301). An allusion that echoes another of the scientific debates at the moment: the significance of the organs atrophy.

Nevertheless, gradualism needs to be emphasized (as, implicitly, it is a superiority feature): «l'art grec

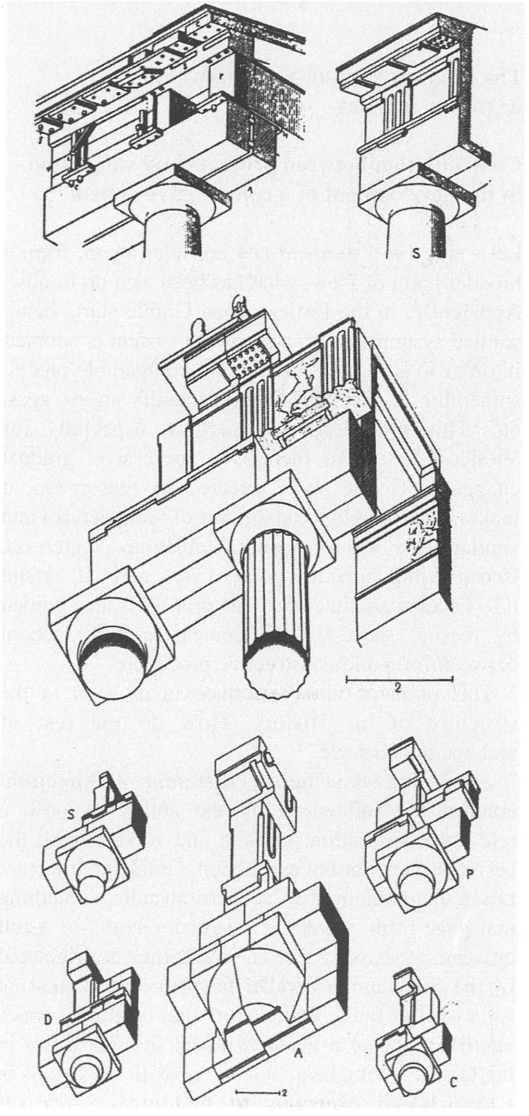


Figure 5
These Choisy's drawings unveil the gradual adjustment of form and rational construction in the Doric entablature

débute par un excès de force et s'approche de son idéal par un progrès continu, non point par une série d'oscillations qui franchissent le but pour revenir en arrière» (I, 309), taking up again the life cycle image that he will use in Gothic: «On dirait un être vivant qui passe sans à-coup de l'enfance à la jeunesse, pour arriver en fin par un pente inévitable à une décadence qui ell-même a son éclat» (I,310).

The role of progressive drawing in a rational history

Confrontation between progress and stagnation in the development of a constructive system

Let's stop for a moment and consider again, from a broader point of view, what has been said up to now. Apparently, in the forties, when Gothic starts being studied systematically, a graphical system is adopted in order to separate a building in comparable pieces, something that should allow to identify styles, ages, etc. This procedure will suggest, especially for Viollet-le-Duc, that there is a successive, gradual change in Gothic style, directed by reason (so, it makes it preferable to other kind of architecture) and similar to a sort of «natural creation». Later on, Choisy will assume this point of view and will extend it to Grecian architecture. This process is also guided by reason, successive refinement and the accord between form and constructive procedure.

This point of view introduces a division in the structure of his History. How do the rest of architectures behave?

According to Choisy, different architectural cultures are influenced by the ability to pose a relevant construction problem and solve it with the best and finest formal expression. Gothic architecture raised the problem of a «new cross vault», something that gave birth, thanks to a superior logic, to a full universe of shapes. Grecian architecture is originated by the challenge to find the best possible expression for a kind of faulty architecture that originally was a «petrifaction» of a wooden model. Its worth lies in the fact of having been able to solve all the details in a «logical and coherent» way.

The rest of architectures raised also essential constructive problems, whose technical and formal solution contributes to defining them. The difference is that they do not achieve the goal of finding a true relationship between construction and formal expression.

In western Roman architecture, for example, there is such a clear gap between form and construction, that the progressions of its expansion and decline periods have a different rhythm (I, 542). In Egyptian architecture, even as Choisy admits vaguely some sort of gradual process, «la variation est lente et continue, mais les formes ont leurs époques, l'art ses alternatives de progrès, d'éclat et de décadence» (I, 81), there is no progressive agreement between constructive form and expression: «Il semble que, dans les architectures primitives, la forme doive tenir à la structure comme l'expression à l'idée: l'architecture de l'Égypte est loin de réaliser dans sa rigueur théorique cet accord entre la construction et la forme» (I, 38).

Stagnant architectures: unsolved petrifaction

What happens in «non progressive» cultures? There is a special feature in architectures of the past that complicate the access to an adequate expression of the constructive form: they tend to originate as a petrified metamorphosis of a procedure in other materials. Choisy collects such a great amount of such cases as to seem this is a general and inevitable process. In primitive epochs, the first brass instruments seem to imitate those made of flint «par un phénomène de survivance bien digne de remarque» (I, 7). Many examples appear in Egypt: the cornice (a transposition of a solution made of cane and clay) (I, 25); sepulchral grottos (an imitation of a wooden gallery architecture) (I, 40); columns (imitating stems, originated perhaps in lacustrine architecture) (I, 41)

Other examples can also be found in Micenic art. In its peculiar columns, one can find «le souvenir d'un Poteau fait d'un tronc d'arbre planté para la pointe», while the entablature «emprunte sa forme au rebord d'une terrasse sur rondins» (I, 234–5). Architecture in India is explained similarly: «la charpente était tellement de tradition dans l'Inde, qu'aux premiers moments où la pierre est employée, la pierre est mise en oeuvre à la manière du bois» (I, 153–4). According to Choisy, this imitation is essentially so «Indian» (everything else would be

Greek, Persian or Chinese added elements) that original wood architecture could be inferred from ornamental stone arches (I, 155). In the same way, lost systems of «encorbeillement» and triangulation could be read (II, 159, 160–1). Even cornices are transference of a clay detail and certain arcades are a copy of a wood solution coming from China.[7]

This problem is such a persistent one, that if a regular process can be observed, it is only that of decadence, of progressive separation between form and construction, as can be found in Egyptian cornices. These are the only «evolutionary» (or rather, involutionary) drawings that Choisy defines for this type of architecture (I, 46).

Races causing the double march of History: evolutionary and petrified architectures

If all this dead weight did not cause a problem to the Greek, why was it not the case for the rest? Why were they incapable of achieving progress in a correct way? There is a racist argument to explain it, an unpleasant aspect that has been unnoticed in most

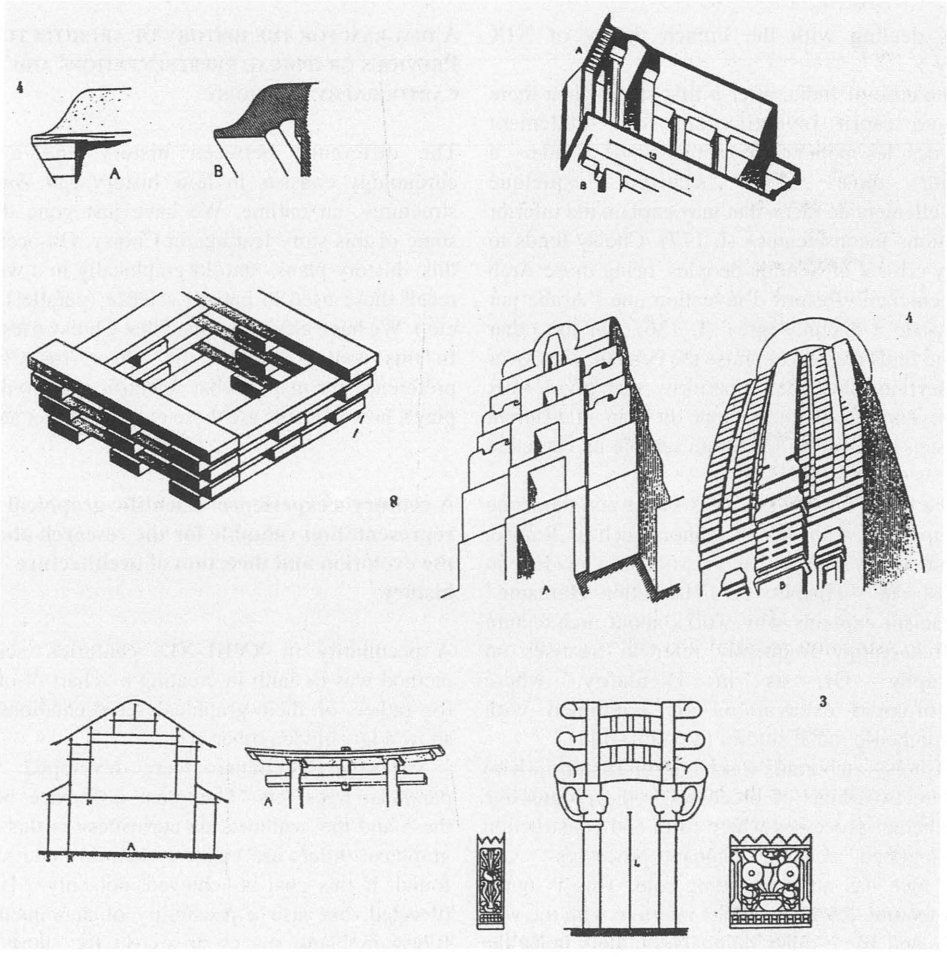


Figure 6
Instances of petrifactions contrived in different cultures that are shown in «l'Histoire

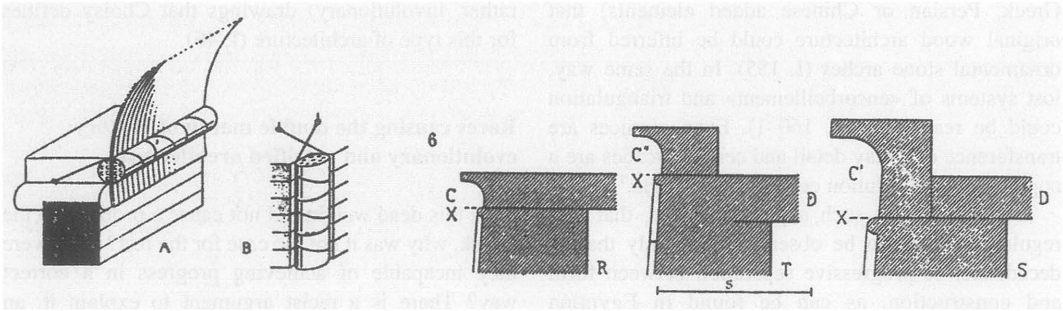


Figure 7
When reason (and race) fails: the Egyptian cornice as a case of progressive degeneration

studies dealing with the French theory of XIX century.

In the case of India, after a first stage when there was «un esprit inventif dont sont totalement déporvues les populations actuelles de l'Inde», a crossing must have occurred, «quelque rénouvellement de race» that may explain the inferior «imitations inconscientes» (I, 177). Choisy tends to be very critical of Semitic peoples, being those Arab or Phoenician: «l'esprit d'invention que l'Arabe pur ne possède à aucun degré» (I, 136). On the other hand, he finds reasons to praise the Persian, who, over the Assyrian, have that superiority that gives «aux races aryennes le sentiment inné du beau, si different de ce sens exclusif du grand qui semble un caractère des races sémites» (I, 119).

To be fair, Choisy's racism is subtle and moderate in comparison with that of authors such as Ramée, Lesueur and Viollet-le-Duc, particularly evident in this last one's Histoire de l'Habitation Humaine.[8] This racism explains why works about architecture and archaeology frequently refer to treatises on etnography. Or, as in Dieulafoy, where archaeological excavations are combined with anthropometric racial studies (. . . 110–111).[9]

So Choisy elaborates a scheme of History where there are two kinds of processes —the progressive and coherent processes where form and construction are integrated, and the stagnant processes— and where race has an outstanding role. This is not a trivial feature. Racist positions interfere with the way Choisy and some other rationalist authors build the development lines of architecture, the «plan» and the «cartography» of the its history.

A DIAGRAM FOR THE HISTORY OF ARCHITECTURE. PREVIOUS GRAPHICAL REPRESENTATIONS AND CARTOGRAPHY IN CHOISY

The difference between history and a mere chronology consists in how history can «have an structure», an outline. We have just gone through some of this story features in Choisy. On occasions, this «history plans» unfold graphically in a way that recall those used in natural science (parallels, trees, etc.). We have also mentioned that Choisy uses maps. In this context, what's the reason for Choisy's preference for maps? what scientific role could they play?, how valuable are these graphs in other authors?

A century's experience: scientific graphical representation valuable for the research about the evolution and direction of architecture history

A peculiarity in XVIII–XIX centuries' scientific method was its faith in creating a «chart of objects» (or rather, of their graphical representations), that show a law hidden otherwise.

So, several schemes were developed: tables, parallels, trees, etc. The great difference between these and the «cabinets de curiosités» is that not all graphical orders are valid, a «natural» one must be found. If this goal is achieved, not only a law gets revealed, but also a possibility of anticipating and filling in blank spaces arises (in the same way it happened with the periodic table of elements). According to this scheme, in the case of fauna and

flora it could be possible to think of the hypothetical existence of a species to be discovered yet, or the possibility of finding a common archetype from which variations arise.

When those displays arranged visually material from different ages, hypothesis about how changes occurred could be put forward, missing links could be detected or future trends in nature could be forecast.

Those chronological displays (parallels, trees, etc.) could be tried in an architecture history, but their explanatory and scientific value is more ambiguous. Only from a very deterministic point of view one could think that any of those schemes would allow anticipating the future (although there are noticeable cases such as Daly's) [10]. Nevertheless, their contributions are significant: it can be useful to show that progress exists in certain fields of architecture, to verify formal lineages, to compare and come to new conclusions when planning, etc.

As we said, the main problem of a «good graphical display» consists in knowing how to select the object of study in history. In principle, at the chronological starting point there could be a comparison of different types of architecture (that is the case of parallels, Leroy), or of different formal preferences (as are unfolded in perspective by Coussin), or something that would be of more interest to rationalists: construction methods.

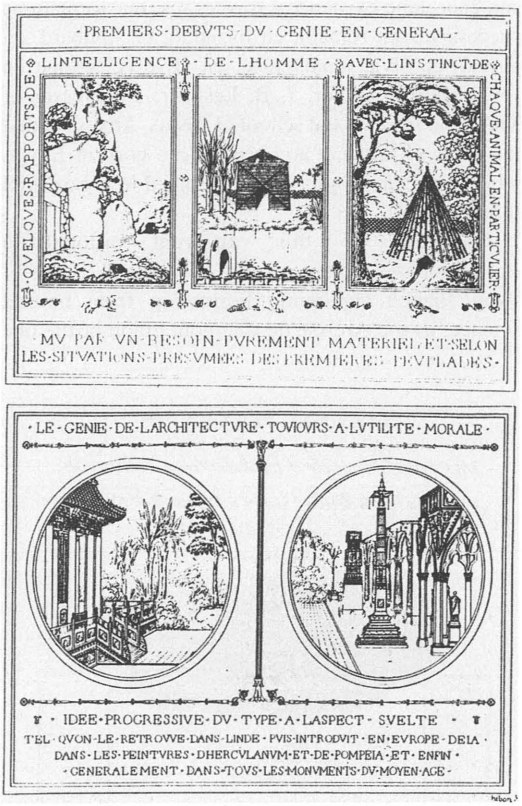


Figure 8
Ways of displaying architectural history. The archetypical models of construction and the different lines of progress according to Coussin

Graphical representations that could be used in rationalistic architecture history (chronological parallels according to constructive archetypes)

In fact, one of the options was to create a history of supposed constructive archetypes of mankind. Coussin's drawings (1822) are already insinuating the possibility of developing this option according to an idea, initially put forward by authors as Quatremère de Quincy, that will be very successful in XIX century: architecture has a triple origin —the hut, the cave and the tent. Men started building by fastening branches and trunks, tying cloths and furs and excavating. Lintel architecture, vaults and domes or tensile architecture (and their supposed derivations, such as Chinese architecture) respectively derive from these archetypical solutions.[11] This argument was so convincing that it succeeded in having an influence in such prestigious naturalists as Cuvier, who assimilated and divulged it.[12]

This must have been an attractive plan for a «rationalist». Starting from this image, a first classification of architecture could be created, with three different and parallel development lines. But this egalitarian scheme got distorted as soon as an archetype was associated with certain peoples, cultures or races, which had different capabilities and progressed at different pace (this idea could lead to tree schemes with a «dominant trunk» as shown in figure 9).

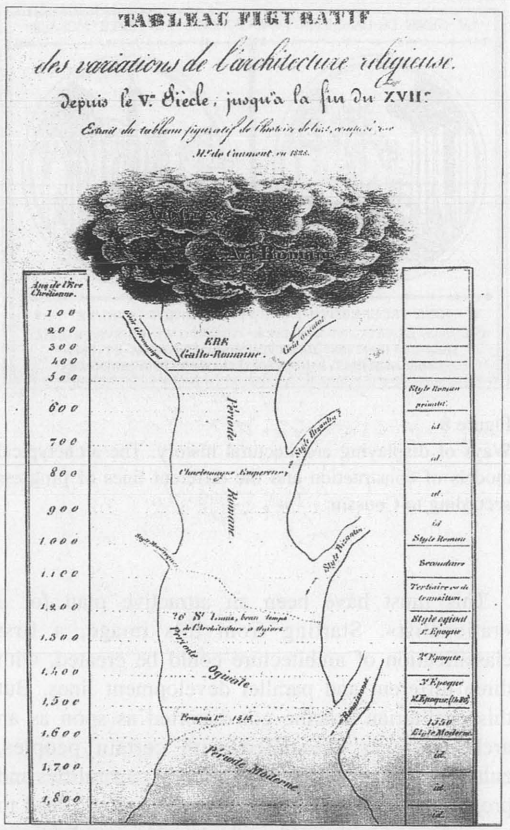
So, for Thomas Hope, *Histoire de l'Architecture* (1852, iii) there exist these three archetypes, but their development is very unequal: «Les deux prémiers, stationnaires et stériles, s'arrêtent aux régions qui les virent naître; le dérnier, progressif et fecund, poursuit

son énergique existence à travers ses transformations successives en romain, en byzantin, en lombard, en ogival, en style renaissance, en style éclectique en fin». Another author, J. B. Lesueur, a professor of Theory at the national school of Beaux-Arts, says that the rules of Grecian architecture are born in Egypt, while China and India are condemned to a perpetual infancy (159).

According to this, different rationalistic «evolutionary» schemes could be outlined. Some of them shaped apparently borrowing from natural science, as the Arcisse de Caumont graph or the one that will appear, in a tree shape, in the Spanish edition of Fletcher (reminding the trees of life by Haeckel).

The preference for cartography in Choisy. From parallel diagrams to maps as instruments for research in History

Choisy's History shows too a racist outline and he's interested in genealogy, but cartographically displayed. So, when he comments on his map of classical Grecian architecture, he says: «aussi bien



45. A. de Caumont, «Tableau figuratif des variations de l'architecture religieuse depuis le Vᵉ siècle, jusqu'à la fin du XVIIᵉ», dans *Cours d'antiquités monumentales professé à Caen en 1830,* Paris, Lance, 1830-1841, atlas, IVᵉ partie « Architecture religieuse du Moyen Age », 1831, pl. XLII.

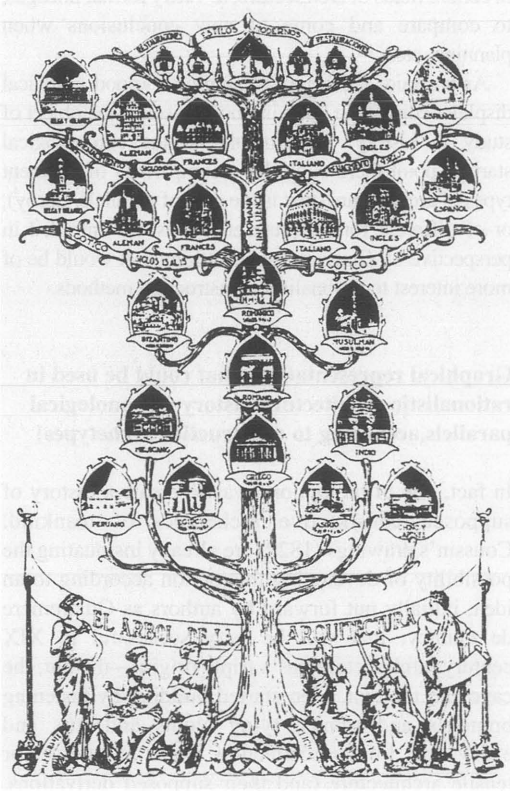


Figure 9
Architectural history as a river or as a tree. Graphics in A. de Caumont's Cours d'antiquités and in a Spanish edition of B. Fletcher's History

que les dialects du langage, ceux de l'architecture sont des titres génealogiques» (I, 506), and «la distribution géographique des styles répond ainsi à la repartition des races» (I, 507) What is the reason for this change from a genealogy in abstract to a genealogy located geographically and displayed on maps?

The first reason is that it agrees better with his rationalism. Choisy thought, as well as the rest of authors mentioned, that the constructive fact had a fundamental importance. But this historical impulse was not a procedure guided by ideal archetypes. In fact, Choisy explicitly shows on many occasions that he knows and rejects this line of argument.[13]

On the contrary, this historical impulse will stem from the invention of certain procedures that depend on a local context to appear —on elements such as the available material resources, the «mental» attitude of the peoples that live in a certain territory, their particular way to organise work. The abovementioned conditions lead to «locating» the architecture in space, they give a geographic character to the «table» of history and therefore, its new graphical display is the map. That way, a new form of «graphical table», the map, is reached.

The second reason is that the use of maps as a new tool for research was already being promoted. When Choisy writes, using and correlating at least three kinds of maps had already been considered or proposed: geological maps, trade routes (or for conquest purposes) maps, and maps for the distribution of an ornamental or typological solution.

A.de Caumont had already asked for a geographical study of architecture history in France, and had pointed at the usefulness that it would be obtained by relating the kind of stone available with the style changes which can be observed when travelling through certain areas (Histoire de l'Architecture, 251–5). In 1855, Viollet-le-Duc developed this idea in an article published in the

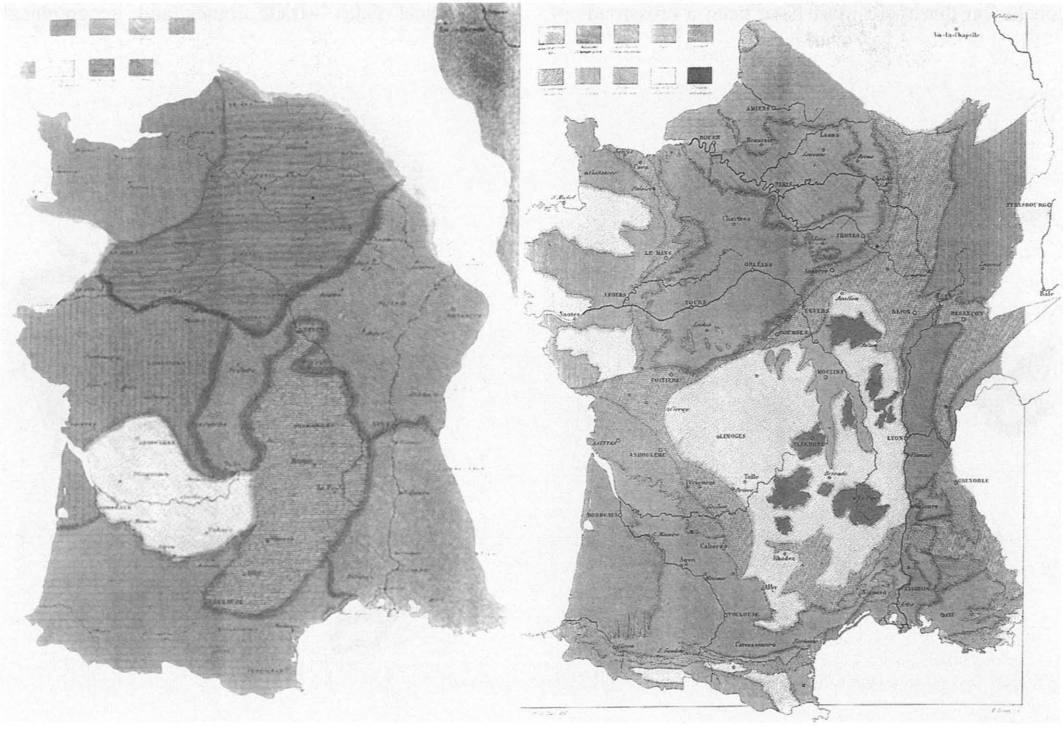


Figure 10
Two maps to be compared: the geology of France and the distribution of architectural styles, both made by Viollet-le-Duc

Révue Générale d'Architecture. There he proposed making a comparative study of the geological substratum in France and architectural styles.

In addition to that, Viollet-le-Duc noticed («architecture» in his Dictionary, 136) that commercial routes of medieval France could be useful to understand the dissemination and utilization of certain constructive solutions. This idea already appears in a treatise by Verneith, who considered the possibility of developing on a map Léo Drouyn's classificatory and typological system: «il serait facile de rendre sur une carte monumentale toute la physonomie de la région des coupoles. De même que des pierres, jetées dans une nappe d'eau, à la fois ou successivement, déterminent une série d'ondulations concentriques, qui s'étendent ou se resserrent, se partagent ou se disputent l'espace» (298).

Choisy seems to have discovered, thanks to Viollet-le-Duc, the possibilities arising from this kind of reasoning, that implies a geographical view. In «L'art de bâtir chez le byzantins» he investigated about where could have originated Byzantine art. He reached the conclusion that there must have been a crossroads of western and eastern trade routes on a Hellenic substratum, because ideas and constructive methods were also transported through such routes. He owed that to Viollet-le-Duc and he recognizes it in a footnote. It is somewhat surprising that he only then discovered the potential of geography.[14] Nevertheless, he would have the opportunity to be more involved with that later on, because when he returned from his travel to the East, in 1876, he took charge of a course on History of Architecture at the École des ponts et chaussées, where later on he would be appointed director of maps and plans.[15]

In his Histoire (1899), this reasoning becomes graphical, with a map where he explains more precisely the dissemination course of Byzantine art (II, 80). There he insists on the argument «l'étude que nous entreprenons tient bien de près à celle de la transmission générale des idées; et comme les idées se propagent par la grande voie de la circulation et des échanges, c'est la carte des courants commerciaux qui nous donnera la clef de ces relations . . . » (II, 81)

Choisy finds out that the correlation between two geographical data —trade routes and geographical

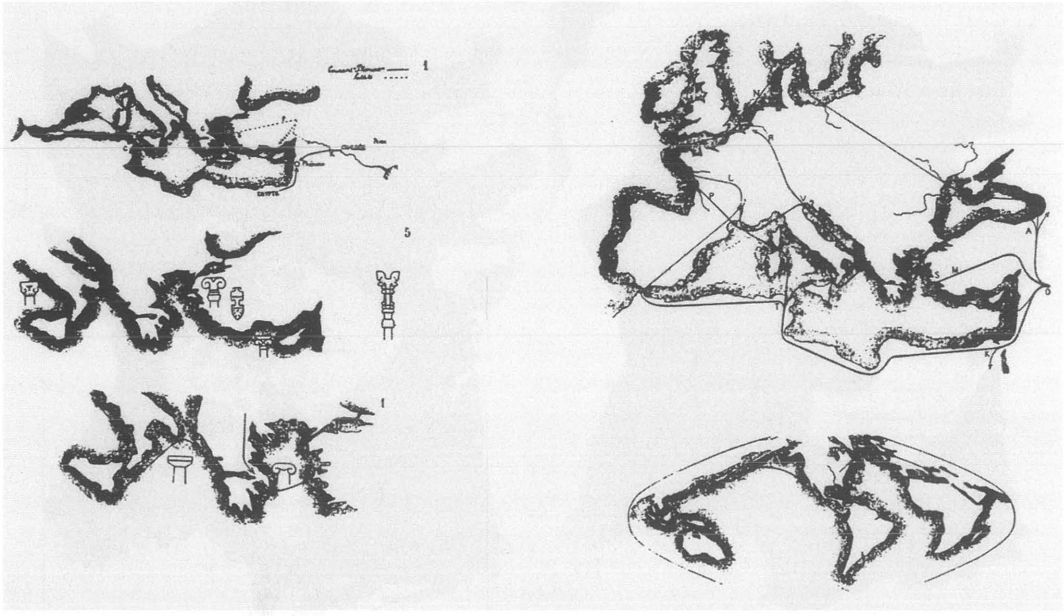


Figure 11
The family tree of architecture unfolded. Some of the maps used by Choisy including one probably indebted to a seminal conversation with Viollet-le-Duc while he redacted his book on Byzantine construction

location of constructive solutions— allows him to make hypothesis about the origin and possible ramifications of apparently similar forms (their genealogy).

In some way, the rest of maps used by Choisy are originated and depend on this Byzantine art map, the first one he created and where he locates Persia as the main source, in coincidence with the racial prejudices mentioned above. Therefore, the study of caravan routes explains how certain architectural elements disseminate from Caldea and Egypt within the Hellenic geographical framework (I, p. 205). Central Asia would also be the remote central point of Mesoamerican architecture, through their previous penetration in Nordic countries (he also ventures an influence from China and Japan).

But the correlation of maps has a wider potential. Choisy discovers the surprising facts that get revealed when comparing two typological distribution maps from two different periods.

It happens so with the «surprising» finding that emerges when superposing two maps: the distribution of Romanic and Gothic architecture in Europe are complementary, «les vides d'un des tableaux répondent dans l'autre aux parties les plus remplies». The graphical method, then, allows to extract new knowledge: «l'impression qui resort du rapprochement des deux diagrames peut se résumer en un mot: les régions où l'architecture nouvelle prospère dès ses débuts sont celles où la place n'était prise par les architectures antérieures» (II, p. 498).

Maps make possible a reflection about the continuity or decadence of irradiating centres. In the case of Romanic and Gothic, allow defining as a historical fact the existence of a gap between Romanic and Gothic.

For Choisy, these maps achieve to build scientifically a genealogical tree: « . . . nous relions les monuments d'une même famille en une sorte d'arbre généalogique exprimant autant que possible leurs attaches mutuelles» (II, 498). A genealogical tree that, when displayed on top of the geography of population migrations, conquest, trade routes or geological resources, turns out to be more powerful and truthful than those outlined in the ideal space of archetypes.

Conclusions

Some provisional conclusions can be reached from this study. Choisy's rationalism considers a superior form of architecture one in which form agrees with construction and expresses it. In this sense, he distinguishes two histories: a «progressive» history and a «faulty» history. Drawing and contemporary science have played and important role in forming and conducting this scheme.

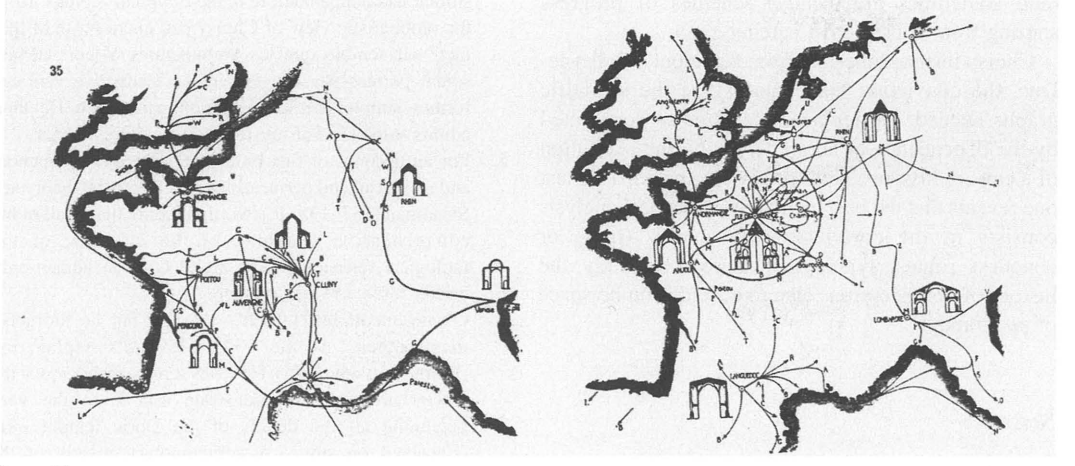


Figure 12
Two maps that when superimposed can reveal historical facts in Choisy's «Histoire»: The centres and dissemination of French Romanesque and Gothic architecture

Progressive architectures (Gothic and Grecian, basically), analytic and evolutionary, find more and more perfect solutions from their starting premises. Their «progressive» solutions can be displayed when comparing graphically several parts of buildings (thanks also to an abstract drawing that illustrates and generalizes a «case»). This kind of procedure reminds those used in natural science. Conceptually, Choisy seems to translate some biology principles (such as the specialization of organs) to architecture. From an ideological point of view, their scientific like drawings are instrumental in demonstrating that when architecture is rational, behaves as nature.

Faulty architectures, even if they start from clever solutions, are not capable of advancing continuously, burdened as they usually are by their dependence on forms not corresponding to constructive solutions (inherited from «petrifaction») and which are repeated by routine. The background for this position is a fundamental substratum (that appears in other authors as well) that connects it with nineteenth-century racism.

Whit this intellectual plan, Choisy tried to outline some sort of global graphical scheme of history.

In XVIII and XIX centuries, the «parallel», the «chronological sequence» and the «tree» were used as a graphical research procedure that allowed visualizing the gaps of a complete order or suggesting the cadence of progress and stagnation in architecture. Rationalist theories outlined verbally (and sometimes graphically) schemes of progress starting from constructive «archetypes».

Choisy instead inherited from Caumont, Viollet-le-Duc, the conviction that maps where the scientific graphs needed. He replaces the impulse constituted by the dependence of an archetype by the resolution of a constructive problem locally originated. This last one reveals that the best method for historical analysis consists in the correlation of «maps» (trade or conquest routes, typological maps): to study the history of architecture is also to unfold it on he space of geography.

Notes

1. Some articles and obituary notices appeared after his death, but two generations passed until the first critical revision was written (Banham, 1960). As it could be expected, his general approach had some gaps and sometimes could seem superficial, but he characterised well the more significant features of Choisy's rationalist approach, and he revealed Choisy's potential influence on modern architects such as Perret and Corbusier. He drew attention to Choisy's relevance. Some decades later, Middleton (1980) published another influential article. More recently Abriani (1991) and T. Mandoul have made new contributions focusing on Histoire de l'Architecture.
2. S. Talenti's excellent work (2000) has served as a reference for the XIX theory, where many of our observations can be set in a context. In her book she pointed out the relationship between architectural theory and the biological sciences that need to be explored more deeply. She is also attentive to the importance of drawing as a tool and a modeller of the mind of the architect in this period. We hope that this paper could be a contribution in the same direction.
3. To explore the influence of natural sciences on Viollet-le-Duc, specifically of anatomy, see Bressani (1996). He finds a sharp difference between Viollet and Choisy in this aspect, alleging the later has been more mechanicist and less attached to an organic comprehension of the architecture. In this paper we try to show that this opposition is not so clear.
4. When Choisy studied the progressive path of capitals forms, he assumed a full rational guided process and, surprisingly, he made room for an irrational «evolutionary force». At the beginning of Gothic architecture, the sculpted decoration of the capital were plant sprouts. At the end of the period matured and full-developed ones were preferred instead. Something similar had happen before in the Egyptian capitals. How the rationalistic view of Choisy can make sense of that fact? «il semble que les architectures à leurs débuts soient portées par une préférence instinctive vers ces formes simples de la végétation naissante». He then admits some kind of mysterious formative instinct.
5. For an account of this biological principle in Spencer and its spread and permeation in architectural theory see Steadman (187–195) It's worth noticing that in all of his comprehensive searching of the influence of the biological sciences in XIX architecture Steadman only briefly refers to Choisy twice
6. Choisy mentions Hubsch's version, but he «forgets» many others, as the Viollet-le-Duc's explanation (Entretiens, vol. I, 45) This was a remarkable «tour the force» aiming to demonstrate that from the very beginning all the details of the Doric temple were conceived on stone. A contemporary review of the many theories that the «petrifaction» problem has generated can be read in Cloquet (23–28) (where he refers to a previous Choisy's article in la Gazette

archéologique (1887, 191) Guadet contributed also an interesting solution (1902, 32–47).

7. At the end of the Century successive historical essays have accumulated a great amount of evidences of the «petrifaction» case. Eventually it was inescapable to think that the process was almost general in the ancient architectures. To explain that, and to integrate it into a coherent ideology of architecture could generate a very complex theory, full of disquisitions as it happen in the interesting section dedicated to «analyse des formes architectoniques» in Cloquet (1901, 9–36). There he displays a variegated panorama of the relations between form and construction.
8. The pivotal argument in Viollet-le-Duc Histoire de l'Habitation Humaine is plainly racist. The centre of the discussion precisely turned on the way each race has eluded or solved the petrifaction. To him is essential to know what are the potentials and the limits that each race shows when faced to an architectonic problem. The inventions that may be credited to the ingenuity of some races are seen as instinctive or unconscious. The Semites «ont inconsciemment donné les éléments de la voûte «(364), in Mexico the stone imitations of the wood structures are made «même inconsciemment» (364), while in China, the construction is a systematic routine that reflects a mind incapable of deductive thinking. That suggests that the ascent from the animal constructions to the archetypical human constructions in Coussin and other authors could be understood as an ascent from the instinct to the conscious, from the animal to the human way of thinking, a scale of mental faculties.
9. See the measures of skulls practised by Marcel Dieulafoy (110–111) as a mean of complementing archaeological data.
10. Daly (1849, 6) y (1869, 10–72)
11. The origin and formation of the theory of the constructive archetypes are investigated in Vidler (1997).
12. Charles Cuvier (1859, 341)
13. Choisy knows very well this issue, but he's uneasy with its implications. For a long time has been assumed that the Egyptian architecture was born in Nubia, and tacked for granted that «l'architecture, originairement troglodyte, se serait peu à peu manifesté au grand jour» (I, 81). But for Choisy this is a mistake not to be afforded after the hieroglyphics had been deciphered. The chronology of the dynasties simply doesn't agree. He rejects also the assumption that the Chinese architecture imitates tensile constructions (as an example of this conviction, Hope (15,16). He neglects also the idea of the gothic architecture as inspired in the galleries of trees of the German Woods, «théorie étrange à laquelle le nom the Châteaubriand donna une vogue momentanée « (II, 513). Instead he can see in the tents of the Assyrian kings the model for «ces cours terminées par des niches couvertes qui jouent un si grand rôle dans les palais assyriens» (I, 109–110). This kind of translations can even be found in the architecture of the Arabs, who «par une habitude de race . . . aient transporté dans leur décoration architecturale les décors de tenture qui avaient été pendant leur période de vie nomade» (II, 110)
14. «Cette vue sur les origines de l'art byzantin, appartient à Viollet-le-Duc. Je l'ai puisée dans une de ces conversations si pleines d'idées et de bienveillance . . . » L'art de batir chez les byzantins (1883, 158, n.1)
15. Annie Jacques preface.

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Wooden composite beams: A new technique in the Renaissance of Ferrara

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M. Russo
C. Alessandri
R. Fabbri

This paper deals with research regarding a singular technique adopted by Renaissance carpentry. The technique consists in the assembly of timbers whose size is shorter than the span to cover (and in some cases the span can be quite considerable).

The resulting composite beam features an arch-like internal mechanical behaviour, which considerably reduce the inflection of the beam.

The following wooden elements (usually three or four) are used to construct the beam:

1. Tie-beam: a single element, located on the intrados, usually curved upwards and mainly subjected to tension;
2. rafters: placed symmetrically at the extrados and subjected to compression;
3. dowel (or key piece): additional central piece whose function varies according to the type of beam.

Two other parts, called «abutments» (4), are designed to give the beam a regular extrados.

The various pieces are connected by notches which allow two contacting components to fit together and prevent them from slipping, and metallic riveting which passes through the entire structure (mainly consisting in nails inserted from the extrados and which feature a riveted point).

In general there are three notches on each side, even if the first (the one nearest the extremity) is hidden because incorporated into the masonry.

This technology is widely distributed throughout Ferrara, and it is not restricted to just the most important

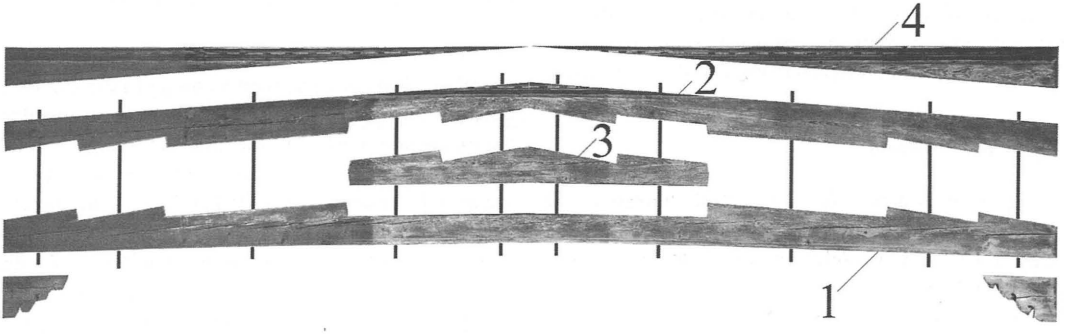


Figure 1

buildings (buildings belonging to the aristocracy, the upper classes and monastic complexes), but it is also found in ordinary buildings. Such widespread distribution is partly due to the good state of conservation of the parts of the city built during the fifteenth and sixteenth-centuries, and is certainly due to historic conditions which determined its large scale use.

The Ferrarese types of composite beam belong to a period which includes the first half of the fifteenth century and the second half of the sixteenth century, during which various techniques were tried and tested resulting in differently shaped composite beams with similar static behaviour.

«Dowelled» beam

This beam essentially consists in two elements: the tie-beam and the dowel. It is achieved by working an entire beam, with the aim of giving the intrados a curved profile. This effect is accomplished by replacing a portion of wood removed from the central part of the extrados with an element called a «dowel», which is longer than the removed wooden profile. The dowel is inserted after the incision made on the extrados has been widened during the curving process. Thanks to this solution, the dowelled beam does not require any notches.

«Three piece» beam

This is the type commonly mentioned in fifteenth-century theorisations and in nineteenth-century manuals.

It consists in three elements which behave like a «truss»: a single tie-beam under tensile stress, featuring notches, and two compressed upper rafters.

In general there is no or a very slight curvature. If present, any abutments are just straightforward finishing touches introduced to regularise the extrados.

«Four piece» beam

This system features four structural elements; the single tie-beam under tensile stress, two compressed upper rafters and a central key piece, which tends to be rectangular.

This type of beam generally features a curved tie-beam intrados.

Given the geometrical configuration of the rafters, the abutements are relatively short as regards length and height.

«Six piece» beam

This is the most mature, widespread and typical in the Ferrarese environment. It consists in the assembly of a (tensile) tie-beam, (compressed) symmetrical rafters and a central key piece. This beam also features a curved intrados and the abutments are higher than the ones found in the other types of beam.

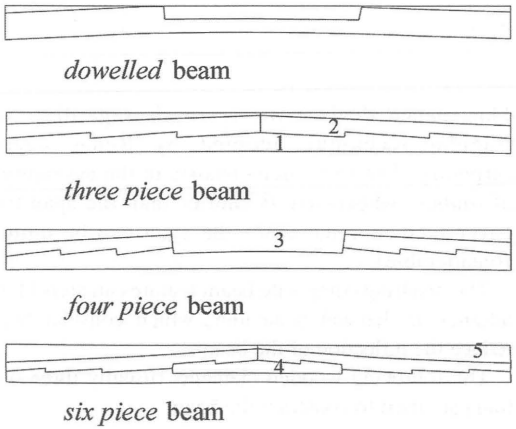


Figure 2
Pattern of the four different type of composite beams with wooden elements indication: 1 tie-beam; 2 rafters; 3 dowel; 4 key piece; 5 abutments

Historic investigation: the local situation

The city of Ferrara was one of the most fertile centres of Italian Humanism as well as home to the Court of the Este family, advocate of a cultural policy linked to the image and prestige of the State. Through a careful re-reading of cultural conquests, the Court was able to grasp at the chance for renewal at the right moment: a symbiosis between *«cenacolo» and «officina»* meant that this transition took place in accordance with the plainly visible inheritance of town tradition, which was gradually innovated from both an aesthetic and a strictly technological point of view.

Thus this «Ferrarese tendency» to modernity is a peculiar phenomenon which, having been able to resist the most «forced» attempts at innovation, has acquired a unique relationship with the local context.

As of the second half of the fourteenth century, through the expressions of courtly life linked to the rural environment, this city nestling in the flood plain of the river Po rediscovers that rapport with the concept of natural space where it is possible to identify the assumptions for redefining urban space.

Structures taper away until they define a construction installation characterised by strong permeability and, especially on the ground floor, by the capacity to integrate with open spaces, translated into gardens, parks, deep loggias: the privileged sites of the new *modus vivendi,* and «places» where the intellectual *otium*, banquets and games are a necessary complement of the construction installation.

The meaning of this special construction, a manifestation of the relationship between building and earth, generates an image of the «suspended» building, where the lived-in volumes are supported by slender structures, a framework consisting in the columns of loggias and courtyards and by a few masonry walls horizontally connected by the main framework of the floors. In this context, walls and boardings become simple curtain elements, whose material effect is further reduced by the application of extensive pictorial and decorative surfaces.

The result is that the section of the buildings (which rarely exceeded one floor above ground level), has a persistently strong horizontal predominance, thus capturing the much sought-after image of peace and relaxation within the same architectural context.

From the first half of the fifteenth century, important buildings gradually began to appear in the city, the homes of noblemen connected to the Court of Este. It is possible to identify the constant presence of a true «spatial fulcrum» in the architecture, consisting in a loggia which looked onto a park or courtyard and which was topped by the main hall. This distribution system offers an element of mediation between the strong effect of continuity on the ground level and the overhanging construction nuclei. In the pattern of the double open loggia, which fully supports the hall on parallel rows of columns and places the areas facing each side of the loggia in direct spatial contact, this solution reaches its maximum level of expression.

On the basis of this concept it is possible to see the creation of prestigious environments of often exceptional size, which required the utmost construction skill and considerable technical ability by the engineers and the carpenters of the time.

For this reason the use of composite beams became a necessary condition and their presence in fifteenth and sixteenth century buildings in Ferrara does not only characterise a particularly significant architectural event, but determines the Renaissance image of the entire city; composite beams are a symbol of extreme technological experimentation and the maturing of construction practices in Ferrara itself.

The following data related to particularly interesting case studies illustrates these concepts:

— in 1435 construction began on the «Delizia» of Belriguardo in the area around Voghiera, just outside Ferrara; the building was conceived as a place for entertaining, and went on to become the centre of the Duchy during the summer months, able to offer the courtiers, gathered around the figure of the Prince, various opportunities for intellectual amusement and physical recreation. Archive documents quote

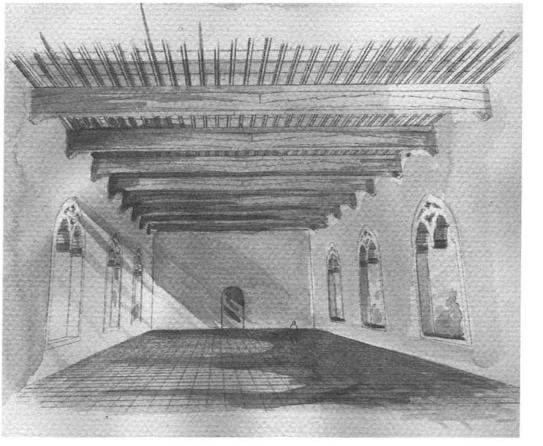


Figure 3
«Delizia» of Belriguardo, Voghiera. View of the original environment of one of the two salons located under the «Sala del Ballone»

the building as being an example of excellent construction expertise, especially for the carpentry used to build the floors of the central building nucleus; here a gigantic hall was built (called the «Sala del Ballone» because it was used for a traditional ball game) located above two grandiose salons measuring 25 m × 15.80 m and about 10 m high. The few and partial testimonies regarding the structure that supported these enormous spaces confirm the presence of composite beams with a transversal section equal to 30 × 90 cm.[1]

— Palazzo Schifanoia is another example of construction expertise. This building was started at the end of the fourteenth century as a place of entertainment and went on to become one of the most important sites of political power during the coronation of Duke Borso d'Este in the second half of the fifteenth century. The palazzo underwent large scale transformation between 1465 and 1469 when the «Salone dei Mesi» was built, located above an ample loggia which linked the main entrance to the rear garden. This audacious structure consisted in 7 «six piece» composite beams covering a span of about 12 m. Unfortunately only a few traces of this structure remain because serious static problems brought about the gradual closure of the open loggia spaces during the nineteenth century.

— On the other hand, Casa Romei (1440–50) preserves its original spatial concept, in spite of the subsequent building phases which have characterised its construction; it is the only case in Ferrara where the double order of porticoes around the internal courtyard has been maintained. The loggia, Figure 5, on the south side of the courtyard (which supports the main hall), is particularly interesting because the ceiling features three different types of Ferrarese composite beam (three, four and six piece beams).



Figure 4
Palazzo Schifanoia, Ferrara. View of the original environment of the loggia located under the «Salone dei Mesi»

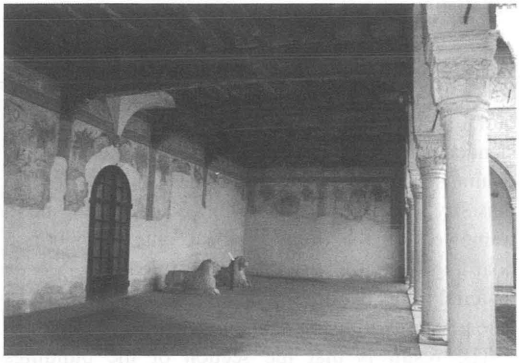


Figure 5

— The main element in the «Palazzo di Renata di Francia» (1475–91) is the double loggia, Figure 6, attributed to Biagio Rossetti, where the use of composite beams has allowed for the enormous space overhead to be suspended on the straightforward pointed structure of the colonnade.

To complete the historic picture regarding the use of this technology in Ferrara, it is worth mentioning the numerous cases of superelevation carried out on religious buildings: the volumes of the large refectories were often divided up by intermediate floors, or the «ex novo» construction of superelevated floors to create halls and oratories. In these cases, the



Figure 6

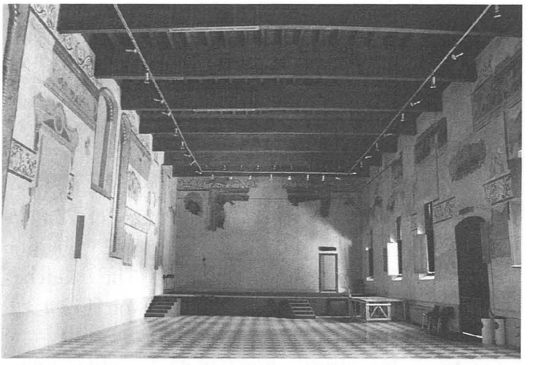


Figure 8
Monastery of San Francesco, Ferrara. View of the refectory

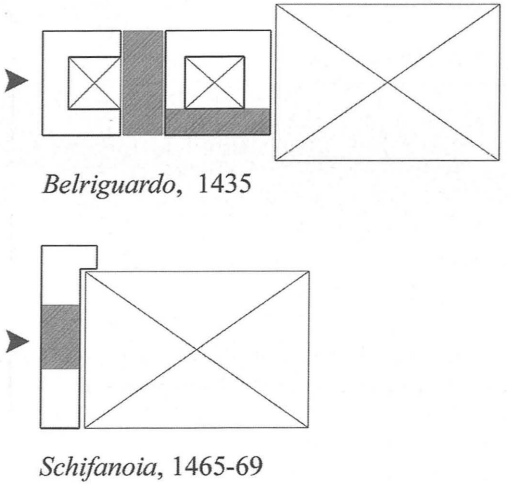


Figure 7

replacement of generally trussed ceilings with flat horizontal ceilings featuring composite beams, often caused a «thickening» of the structure which subsequently reduced the interaxis and required additional bays to support the new loads.

Analysis of the sources

A more far-reaching research, based on the study of documentation from the fifteenth to the seventeenth centuries and nineteenth century manuals, places the first experiments using composite beams in construction at the first half of the fifteenth century.

Nevertheless, the first examples of wooden composite systems expressed on paper date back to the *De Architectura* by Vitruvius: Roman building techniques included the use of joints shaped like «freccia di Giove» applied to the «Opus Craticium» system and the use of coupled beams which had the task of increasing the strength of structures covering large spans.

The oldest graphic representations of composite structures, created to overcome the problem of finding suitable material to cover exceptionally large spans, belong to the Gothic age and can be found in the drawings by Villard de Honnecourt (first half of the thirteenth century).

The concept of the composite beam finds its first specific reference in the *De Re Aedificatoria* by Leon Battista Alberti, finished in about the mid fifteenth century; no specific terminology is employed, but there is an attempt to describe the mechanical behaviour of an element made up of multiple parts and designed to cover large spans:

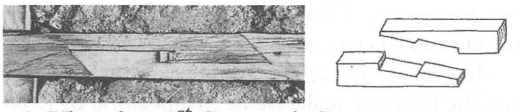
«Sin autem erunt arbores minores, quam ut queas integram unico ex trunco trabem ponere, plures in unam compacturam coagmentato, ita ut in se arcus vim obtineant, hoc est, ut superior compactae trabis linea fieri nequicquam possitponderum pressura brevior, et contra inferior linea fieri haud possit longior, sed quasi corda ad superadactos, qui sese contrariis frontibus protrudant, truncos obfirmandos nervoso sistat captu.» (Alberti 1485, liber 3, XII)

The passage by Alberti highlights how the static behaviour of a composite beam made up of three appropriately assembled wooden elements provides a «simple truss» effect, where the applied loads are transmitted directly to the constrained extremities, considerably reducing the inflection of the beam.[2]

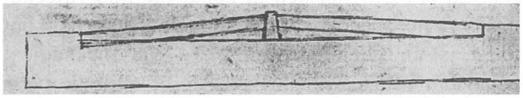
The sketches by Mariano di Jacopo from Siena (called «il Taccola»), included in the *Liber tertius de ingeneis ac edifitiis non usitatis* dated 1433, take on special significance in this regard. The sketches include the very first direct reference, even if in a still intuitive form, regarding the possibility of transferring the «truss» function to a ceiling beam, thus considerably reducing the slope of the rafters and the size of the king post.

It is not possible to confirm with any certainty that the beam described by Alberti is a development of this structure of still dubious load-bearing capacity; nevertheless the design of a much lowered truss seems to be the most convenient way of composing a single beam made up of various pieces.

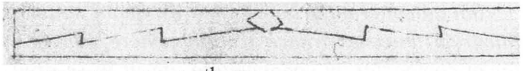
The fifteenth and sixteenth writings by Leonardo da Vinci, included in the *Codex Atlanticus,* contain numerous notes on the theme of composite beams. It is possible to observe the continuous attempt (repeated in various manuscripts) to find new ways of building a beam made up of various pieces, most of which slotted into each other. The subject of Alberti's investigation re-appears in a series of experiments regarding the different ways in which a wooden element can be curved; Folios 91 Verso and 139 Recto include four piece beams very similar to those already in use in buildings in Ferrara during the 1430s, Figure 10.[3]



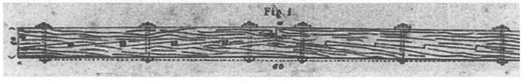
1. Vitruvius, 1st Century b.C.



2. Taccola, 1433

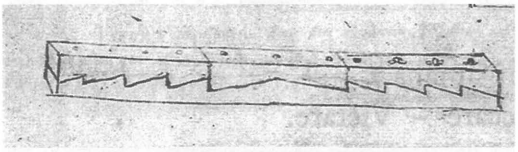


3. Di Giorgio, 15th Century

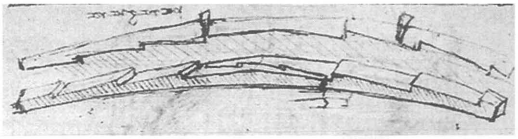


4. Breymann, 1884

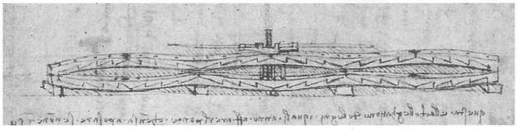
Figure 9



1. Leonardo, *Codex Atlanticus*, f. 139r.



2. *Ibidem*, f. 91v.



3. *Ibidem*, f. 917c-r.

Figure 10

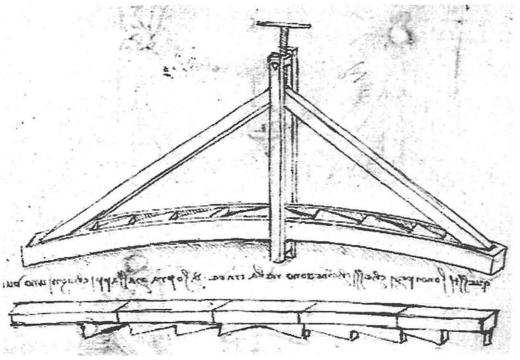
The studies by Leonardo da Vinci tend to research aspects regarding construction techniques, such as the possibility of physically impressing the curvature on the tie-beam, how to cut notches and how to connect the various components.

Leonardo draws tools, which he probably thought up himself, useful for carrying out these tasks; in particular more than once there is a sketch of a trestle, Figure 11, made up of two slanting planks (rafters) and a worm screw, used to transmit the necessary force to the tie-beam and thereby causing it to curve.

He carries out in-depth research regarding the construction processes used to build the composite beam; the drawings are accompanied by comments:

«Piegalo prima, po» lo «ntaglia e fa che desse intagli siano disegnati col fil piombato, e commetti innanzi ch'esca da la vite.» (Leonardo, f. 946r.)

On the basis of these important contributions, nineteenth century Manuals, and Breymann in particular, offer detailed and exact descriptions of



Leonardo, *Codex Atlanticus*, f. 91v.

Figure 11

construction geometry: how to cut notches and the proportions of each single piece. The layouts given by each author do not widely differ, the only difference is the degree of detail used to reproduce the main dimensional ratios; these were obtained not only by considering the geometry but also on the basis of static computations. The single parts are generally fractions of the span, of the height or thickness of the beam and, in the most detailed drawings, strict relations appear between the different heights of the tie-beam.

The constant reference made to a curvature impressed on the beam during the very first work phases links the descriptions outlined in the manuals to Leonardo's handwritten notes. The curvature was impressed on the piece of wood before the notches were cut, whereas it was only released once the entire connection process had been carried out, thus providing the element with an initial stress state.

Technological analysis

The study of historic building methods and the interpretation of historic construction phases have made it possible to define the evolution of the composite beam. This is confirmed by the possibility of recognising in the geometry of the various types of composite beam, the presence of proportional geometric patterns used to model the pieces to put together.

Distribution through time of the different types of composite beam

The distribution of the beam typologies through the whole city, related to different historic periods, highlights, as a first stage, beams belonging to the

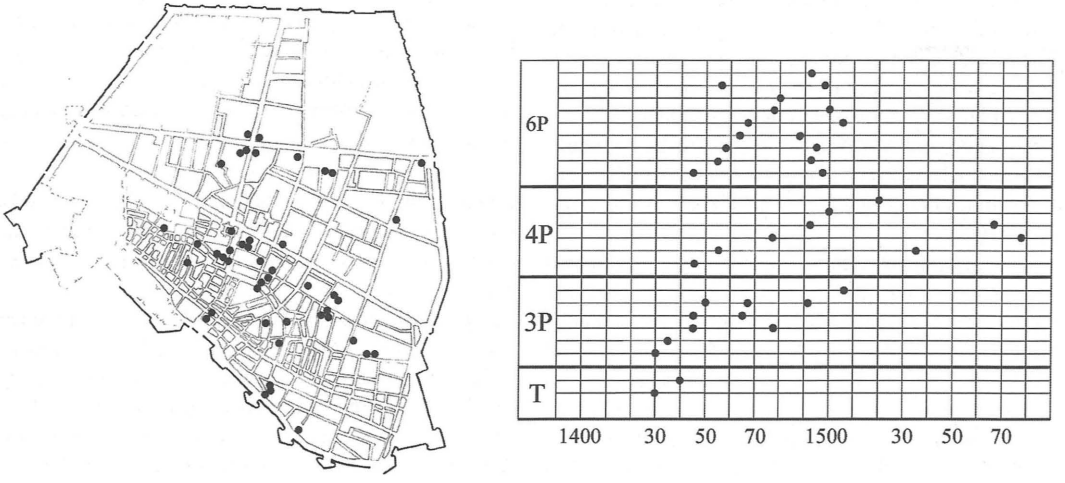


Figure 12
Plan of Ferrara and chronological table which show the diffusion of composite beams in Ferrara between the 15th and the 16th century

«dowelled type», which theoretically preceded the more mature «four piece» beam.

During the years between the second half of the fifteenth century and the first half of the sixteenth century, the «six piece» beam was mainly used, especially in the most important buildings, where it was necessary to cover large spans or where «serial» use was made of the beam system.

Therefore, starting from the initial experiments, the widespread use of this technique allowed the achievement of a mature phase during the age of Biagio Rossetti, marked by a strong standardisation of the typology and by the development of the special characteristics which allow one to talk of a «Ferrarese beam».[4]

Structural indications present in the documentation

On the basis of studies into Renaissance documentation, two different interpretational «patterns» have been defined as regards the beam-typology and its behaviour.

The first appears in the document by Leon Battista Alberti and reports the «triangular» behaviour of the «three piece» beam, or the triangular layout of the forces.

The same structural pattern appears in the drawing by Taccola, who perceives the possibility of its application to a straight beam based on the plan of a «lowered truss» beam. The migration from the «reinforced» beam solution to a composite beam with a constant section is entrusted to the more extensive use of notches between the contact surfaces.

Leonardo da Vinci draws a composite beam whose main characteristic consists in the curvature of the tie-beam and which coincides with the Ferrarese «four piece» beam.

The different structural interpretation of the two authors regarding the «truss» behaviour and the «arch» behaviour strengthens the theory of a «double genesis» and the parallel development of the composite beam in Ferrara during the same period. The «six piece» beam represents the most complex and refined type of beam, which combines the two approaches described by Alberti and Leonardo. In this complexity it is possible to identify the result of the evolutionary timelines which developed during the fifteenth century.

Construction phases of the composite beam

Research into the historic construction of composite beams based on the documentation allows us to identify the construction methodology used by the Ferrarese Renaissance craftsmen and gives a more profound insight into the woodworking techniques employed.

The production phases used to construct the beam can be summarised into four categories which can be assumed as constants for the types of beam identified:

- Curving: the inflection of the tie-beam.
- Shaping: design and creation of the notches on the tie-beam, rafters and key pieces.
- Assembly: the correct setting up and fitting together of the various parts.
- Riveting: permanent fixing procedure, after which the beam can be said to be complete.

Curving: The reference document is the *Codex Atlanticus,* wherein Leonardo da Vinci suggests the «trestle» solution for the «curving process».

In this solution the tie-beam is curved to create an internal stress state throughout the composite beam; but this poses practical problems as regards the procedures to be employed, making the formulation of further theories necessary. In particular, the possibility is pondered of permanently deforming the tie beam using heat and steam near the middle, a technique used in the shipbuilding industry of the time.

Different structural behaviours and construction technologies apply to the different curving procedures.

Shaping: According to the indications by Leonardo da Vinci, the tie beam must be shaped when the curving has been completed; in fact this provides very regular surfaces on which to place the other components, thus allowing the pieces to fit together perfectly without the need to insert other elements.

But it is possible to speculate that the shaping process of the tie beam takes place in two distinct phases: one before the curving procedure to create the housing for the central key piece, and a second phase, when the notches are cut into the curved wood.

The assembly of the curved tie beam and the upper pieces (the undeformed rafters and key piece), poses

geometric problems as to the possibility of juxtaposing the parts correctly.

In spite of the scant indications, the stages described by Leonardo da Vinci and later nineteenth century elaborations, it has not been possible to accurately reconstruct the most commonly adopted procedures used during the Renaissance to solve these problems.

Assembly: During this phase it is possible to hypothesise the use of a stratagem as indicated in the nineteenth century by Breymann:

«The two upper pieces are placed on top of the lower piece, while the lower piece is maintained curved, the lower piece is then curved even more, not only so as to insert the upper pieces more easily but also to give more strength to the shaped joints.» (Breymann 1884, 2: 16–20)

The author refers to a further slight curving of the already curved tie-beam which has the aim of enlarging the housings thus making assembly of the upper pieces easier.

The subscquent removal of the additional load allows for an improved and more efficient contact between the pieces, as well as creating an internal state of stress, resulting from the contrasting action exercised by the upper elements.

The cause providing the inflection to the tie-beam is then removed and it is only during this phase of the process that it is possible to contemplate the application of the so-called «abutments» necessary to create a perfectly horizontal extrados.

Riveting: This operation foresees the use of large nails (approximate section of the head: 2 × 2 cm) inserted to connect the structural parts: this guarantees the absence of any differential displacement between the parts. The nails were driven downwards until the point of the nail completely emerged. The point was then riveted at the intrados.

After this the abutments (fixed only by riveting) were applied using smaller nails which only passed through the rafters.

The number of normally observed rivets is one for each notch, mainly located in the middle of two successive notches.

In general the nails are aligned along the geometric axis of the entire beam, unlike present-day mixed wood-steel structures.

Proportional patterns

Over the centuries, the quest for a reliable «rule» which could be repetitively applied to structural sizing has called for the coding of proportions. Experimentation has suggested the necessary variations or refinements needed to obtain results of the desired quality. The parts making up composite beams have also been sized according to the laws of geometrical proportion, applicable to each case thanks to straightforward changes of scale.

This coding has left traces in recognisable evolutionary timelines, where partial modifications to geometrical patterns do not only reveal the development of the technology itself, but also indicate which aspects of static behaviour of the beams the *inzigneri* (engineers) and *marangoni* (carpenters) focused their attention on.

The span in particular is divided by way of a modulus equal to one third of the span; central key pieces correspond to this modulus as well as the rafters in «four piece» beams.

A similar rule is applied to the shaping of the rafters, whereby the internal notches are distanced according to moduli equal to 1/9 of the total span. This rule is maintained in the first formulas for the «six piece» beam, while in the «three piece» beam, for obvious geometric differences, the division into thirds gives a modulus equal to the value of 1/6 of the total span.

The initial assumption of constant moduli is followed, on the basis of experiments carried out mainly on the «six piece» beam (the results of which were soon applied to the other beams), by the scanning of the notches using a «progressive step»; as regards the geometry described, the notches were moved back towards the supports by a further modulus equal to 1/3 (1/27 of the total span) resulting in the geometry indicated in the Figure 13.

This solution highlights the desire to improve the transmission of the internal forces between the rafters and the tie-beam in areas nearer the supports, thus reducing the flexional effects on the beam.

The comparison between division «by thirds» of the main geometries and the scanning «by quarters», adopted at a certain point in drawings of the key pieces in «six piece» beams, highlights the influence exercised on this construction technique by the units of measurement in use at the time. The main unit of measurement, the *«Piede»* (Foot), was divided into quarters; each quarter

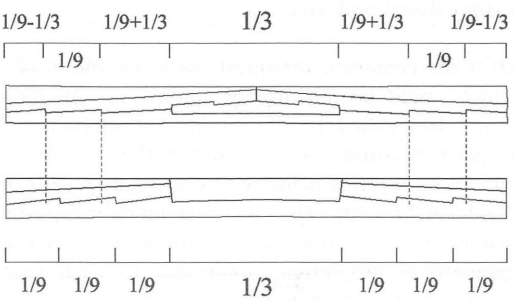


Figure 13

was called a *«Palmo»* (Span). Each span was divided into thirds, called an *«Oncia»* (Ounce).

Therefore, thanks to these historic measurement units and their specific values in Ferrara, it has been possible to reinterpret the type of sizing scales employed, and verify their use with utmost precision in fifteenth century buildings.[5]

Conclusions

This research has allowed information to be collected and compared (in part new and in part already known), relative to a special building technique using wooden composite beams, proof of the high degree of technological refinement achieved in fifteenth century Ferrara.

In particular, production and assembly techniques applied to the wooden elements have been re-discovered as well as structural behaviours and rules of proportion between components, memory of which had been lost in time. This investigation has been carried out on the basis of interdisciplinary contents which, when compared with each other, have offered utterly new results.

Notes

1. The theories regarding the geometry of the beams and the number of parts are based on research into other building sites in Ferrara and examples from Renaissance documentation; there are also obvious analogies with the floor of the «Sala dei Gigli», built in 1472 in Palazzo Vecchio, Florence, whose structure is made of composite beams with a section equal to 105 × 30 cm covering a 15.85 m span.
2. A drawing on the margin of a page in the manuscripts by Francesco di Giorgio Martini (end of the fifteenth century), reproduces the «truss» system described beforehand by Alberti, enriched by the notches shaping.
3. In 1438 Alberti establishes relations with Ferrara and it is very probable that his presence at court also included consultations. The treatise (dedicated to Lionello d'Este and probably ended in 1452), did not start before 1443, the year in which Alberti left Ferrara and returned to Rome. As far as the authors know it does not seem possible, given the lack of reliable sources, to establish where and when Alberti was able to see the «truss» system, or whether it was his own original contribution to architectural practices; it is only possible to observe that in Ferrara the first cases of the «three piece» beam date back to the 1440s–1450s (the portico of Casa Romei). As concerns Leonardo, he may have passed through Ferrara after the fall of the Sforza in 1499, on his return from Milan to Florence, when it has been proved that he made intermediate stops in Mantua and Venice and thereby may also have stopped off in Padua, Ferrara and Bologna.
4. The architectural example of Casa Romei includes three different types of beam belonging to the same historic period. This demonstrates the presence of the distinct types of beam in their primitive form from the first half of the fifteenth century. The typological transformation process can therefore be seen within each single type of beam.
5. For an example, a 96 spans beam pattern, corrisponding to 9.67 meters, could be divided in three parts, 32 spans long; each of these could be simply subdivided in three part of 32 ounces, thus obtaining the initial «constant step» scanning of the notches.

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On the art and the culture of domes. Construction in Milan and Lombardy in the late sixteenth and in the first half of the seventeenth century

Irene Giustina

In absence of objective and universally accepted knowledge of statics, the construction of domes seems to have represented, until at least the end of the XIX century, one of the most difficult problems for architects and builders.

The moment of the undertaking of domes —apart from the formal and the expressive purposes, the selected geometry and the building techniques, the involved human and economical resources— often led architects, owners and building yards to cautious pauses, that could even last centuries, implying the re-examination of the original plans, or sometimes the reconsideration of what was already built, or even the settlement of completely different projects.

The large number of damages and the frequent ruins of vaults and domes that marked the course of architecture in history testify the objective difficulties met by the builders in the comprehension of the behaviour of those coverings. The builders were supported only by practical experience and uncertain sizing rules, mainly of geometrical kind, that varied according to the problem they had to deal with and to the cultural environment.[1]

This lack of homogeneity made systematic studies about domes planning and building very difficult, and such a study is currently still missing in regard to the areas of Milan and Lombardy.[2] In this context, the present work considers as a starting point the vicissitudes —very important to the architectural debate in Milan— concerning the reconstruction of the dome of the early christian basilica of S. Lorenzo,[3] ruined in 1573 and re-planned by Martino Bassi, figure 1, and the dome of the church of S. Alessandro, built in 1626 by Lorenzo Binago and demolished in 1627,[4] figure 2.

Through the examination of the archival documents, the proposed plans and the executed interventions in these two milanese buildings, the present paper intend to fulfil a first general outline of the planning aspects, the construction practice and the understanding of the behaviour of masonry domes in Milan architecture between the second half of the XVI and the first half of the XVII century.

During this historical period, that largely coincides with the counter-reformation activities promoted by



Figure 1
Milan, S. Lorenzo, back view of the church.

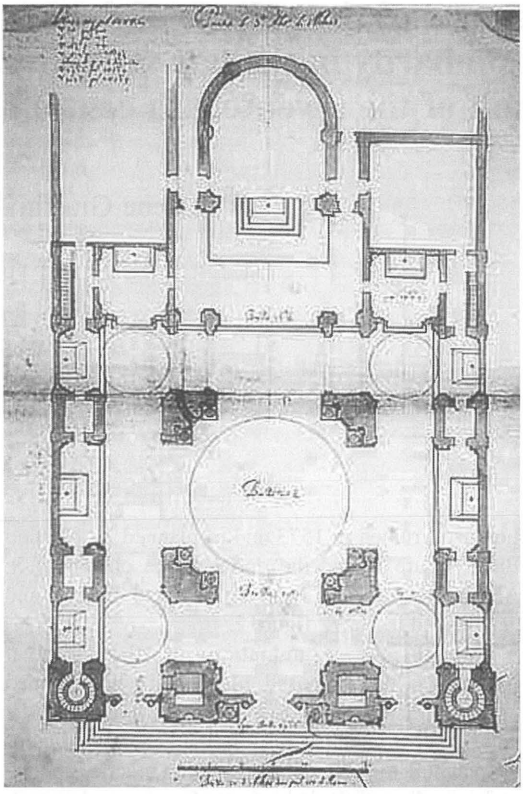


Figure 2
Lorenzo Binago, ground plan of S. Alessandro, 1602, Milano, Archivio Storico Civico, Raccolta Bianconi, VII, 6.

the archbishops Carlo and Federico Borromeo, many building yards of important churches in which domes were foreseen to cover the ecclesiastical plan system, or its most significant spaces, were opened in Milan.

According to a habit deeply rooted since late antiquity, the local architectural culture preferred, rather than the extradoxed domes, the solution, so traditional as to be called «alla lombarda», of the dome covered by «tiburio», crowned or not by a lantern.

Limiting our observations to the context of Milan and recalling only the most famous examples, domes with «tiburio» may be found in many late antique buildings, such as the S. Aquilino chapel in S. Lorenzo (and probably the original dome of S. Lorenzo itself), in the carolingian sacellum of S. Satiro, in the romanesque church of S. Ambrogio and in many other buildings belonging to the mediaeval period.

During the Renaissance, the «tiburio» solution was again widely adopted, preserving the inherited mediaeval building tradition and classically renewing its architectural language. The structural and stylistic problem of the «tiburio» of Milan cathedral, left then unsolved, raised an ample debate in 1487–88. In that occasion, in addition to the local builders, also Bramante, Leonardo, Francesco di Giorgio were invited to propose a plan. Bramante, who would have designed in Rome, for St. Peter, a partially extradoxed dome recalling the model of the Pantheon, in Milan covered with «tiburio» the domes of the church and of the sacristy of S. Maria presso S. Satiro, and the dome of S. Maria delle Grazie. Between the end of the XV and the first half of the XVI century, the «tiburio» was used in all the major religious buildings in Milan: among the most important those of S. Maria presso San Celso (begun by Dolcebuono in 1497), of the Trivulzio chapel in the church of S. Nazaro in Broglio (begun by Cristoforo Lombardo, ended in 1547), of S. Maria della Passione (begun by Cristoforo Lombardo in 1549–50), figure 3, of S. Vittore al Corpo (Vincenzo Seregni, 1559; ruined and rebuilt by Pellegrino Tibaldi, 1568–about 1573) may be recalled

Since the late Sixties of the XVI century, in Milan, the tradition of «tiburio» begun to encounter a first crisis. The influence of the roman architectural trends, that proposed the partially extradoxed dome – connected to the model of Pantheon and of the Bramante's plan for St. Peter —as well as the entirely

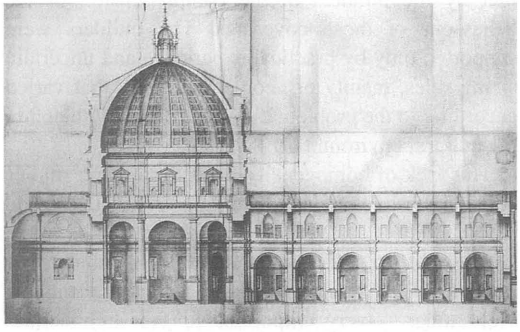


Figure 3
Milan, cross section of S. Maria della Passione (1549–50).

extradoxed dome— connected to the model of Michelangelo's St. Peter —gave rise to the first openings that introduced in the local architectural culture a strong dialectic between tradition and change.[5]

It is likely that the first wide use in Milan of the extradoxed dome, crowned by a lantern and superimposed on a drum with windows was due to Pellegrino Tibaldi. He actually proposed this kind of solution in S. Fedele (1568–69), figure 4, in S. Sebastiano (1578–1586) and in the Sanctuary of Caravaggio (1571), even if he did not disdain the «tiburio», used for example in S Vittore al Corpo.[6] Around 1590, the projects designed for S. Lorenzo dome still wavered between the «tiburio» and the extradoxed solution. During the first half of the XVII century many domes with «tiburio» were still planned, such as the dome of S. Alessandro, built by Binago, figure 5, and almost every dome built by Francesco Maria Ricchino, one of the most important architects in Milan in that period. Nevertheless, Ricchino seems to have made a few exceptions in some plans, left unexecuted, such as the one provided for the dome of S. Alessandro, designed following the roman style (1629–30) (Giustina, 2002), *figure 6*. In contrast, it could happen that extradoxed domes were covered with «tiburio», as occurred to Tibaldi's dome of S. Sebastiano (Fabio Mangone, 1628).[7]

The incapacity to take a definite direction was probably due, besides the aesthetic problems, to the great structural difficulties related to the new types of domes. Lombard architects and builders were actually scarcely familiar with the new structures and with their statics. Their worries especially increased in presence of a dome supported by four main arches and pendentives, superimposed on four free-standing pillars. That was considered in the past one of the most difficult engineering problems, and that was the kind of structure that could be found in S. Lorenzo, with a late antique 'double envelope' plan, figure 7, and in S. Alessandro, with a *quincunx* plan, figure 2.

The study of the documents regarding S. Lorenzo and S. Alessandro[8] makes clear that one of the main problems of the builders was the determination of the size of the piers in relation to the evaluation of their strength. The debate on S. Lorenzo dome proves that at the end of the XVI century it was intuitively very clear for milanese builders that the pillars should basically resist to two different kinds of stress, ensuring strength to the superimposed weight, that is to compression and bending, as well as to the thrusts of the dome, that is to tilting.

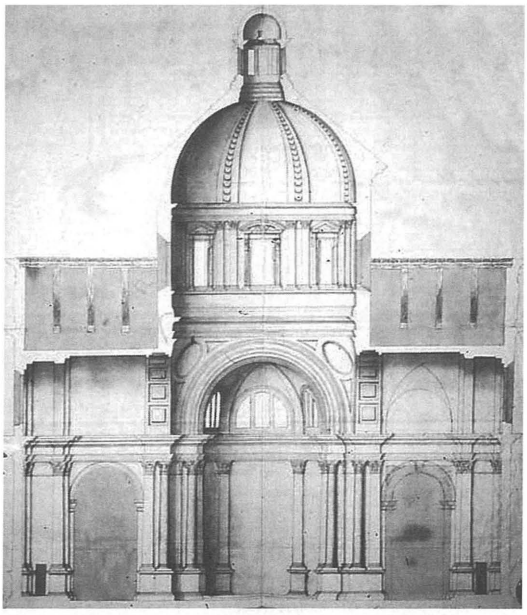


Figure 5
Lorenzo Binago, transverse cross section of S. Alessandro, 1602 (?), Milano, Archivio Storico dei Barnabiti, Cartella Grande I, mazzo I, fasc. III.

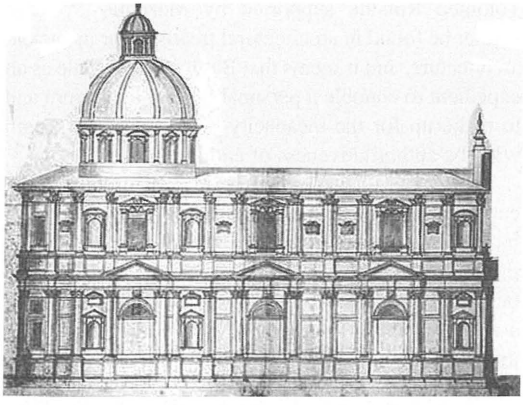


Figure 4
Copy of Pellegrino Tibaldi's project of the side of S. Fedele in Milan. Milano, Archivio Storico Civico, Raccolta Bianconi, VI, 12.

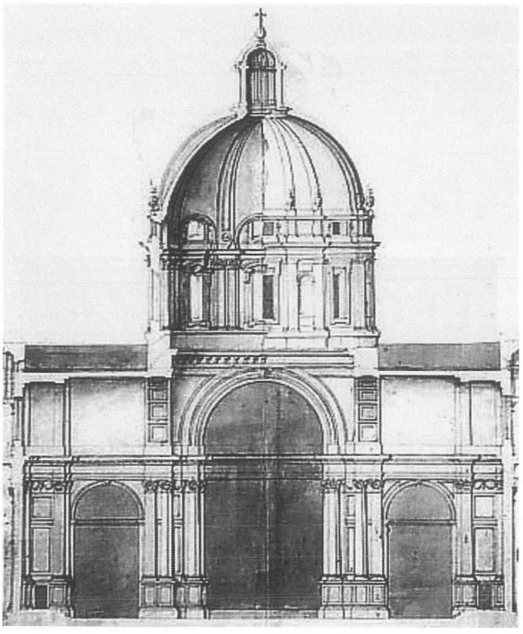


Figure 6
Francesco Maria Ricchino, transverse cross section and partial front view of the new dome of S. Alessandro, unexecuted project. Milano, Archivio Storico Civico, Raccolta Bianconi, VII, 13.

The builders tried to solve the problem of resistance to compression and bending, which could arise «per la grandezza materiale del peso al ingiù quando la forma, et la matteria del resistente, no' superasse il soprapostovi di forza»[9] (because of the great vertical weight in presence of inadequate buttresses), by the choice of appropriate building materials and techniques. In S. Lorenzo Bassi reconstructed the ancient masonry pillars covering them with squared local stones, «ceppo» and «serizzo».[10] The certainty of the stones being higher in strength than the bricks was justified by the firm belief that the strength of materials was proportional to their weight, and so «il ceppo è di forza maggiore del cotto, nella proporzione che è più grave del cotto».[11] The documents regarding the dome of S. Alessandro furthermore show that the builders were also concerned about the bonding of the building materials that formed the pillars. Binago recommended to wall up well and to connect by iron

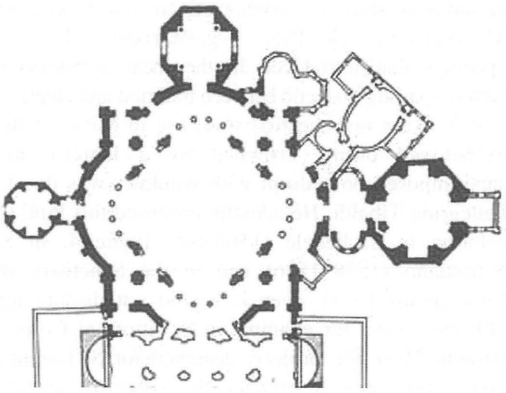


Figure 7
Milan, S. Lorenzo, ground plan.

cramps the marble covering blocks with the masonry core, «ben murati et incambrati con grappe di ferro».[12]

The rule, observed by Bassi, for the size of the height of S. Lorenzo pillars according to the superimposed weight seem to be rather curious: Bassi tried to get over the doubts of the supervisor of the yard, Guido Mazenta, with the assumption that the strength of the piers should be related to the number of the architectural orders that could be superimposed on them, diminishing the height of the orders «in sesquiquarta porzione », that is by 5/4.[13] However, this assumption —as Bassi was told by the roman architect Tolomeo Rinaldi, supported by Mazenta—[14] could neither be found in architectural treatises nor in ancient architecture, and it seems that Bassi used this rule as an expedient to ennoble a personal building criterium and to make up for the incapacity of calculating strength with the authoritativeness of antiquity.

The hint at the «motto laterali o' da archi o' dalla cuppola, quando no' havessero li resistenti, et li incatenamenti bisognevoli»[15] (literally, the sidewise movement of arches and domes in case of inadequate buttressess and ties) makes clear that on the ground of a right structural intuition, based on experience,[16] in the architectural culture of the second XVI century the behaviour of vaulted structures and their spread, which would tilt the piers in absence of adequate buttresses and ties, was well known.

In S. Lorenzo the four towers that were at the corners of the square plan —«li muri che li

contrastano in linea retta formando il quadrato che serra e include tutta la struttura e che forma le torri»— were considered by Bassi as the main buttresses of the domed core. For this reason, the architect planned to reconstruct them stronger and, above all, taller than before «non solo nelle parti reputate guaste ma anche fino all'altezza della cupola, come dal progetto stabilito (. . .) per assicurare ed abbellire l'esterno della fabbrica»[17].

It is widely known that the use of ties —although openly criticised by official architectural culture and taken, even by Bassi, as a reason to criticise what Tibaldi had done in the baptistery of Milan cathedral— was never neglected in building practise (Della Torre, 1990). At the same time, it was also considered that the most positive effect of chains, were they iron made or wooden, placed in the intrados or in the extrados of vaults, could not be obtained without an excellent workmanship brickwork. Only in this way it could have been assured the best behaviour of masonry, which, bonded at its best, would have thus turned into a homogeneous, and therefore resistant, material.[18]

In S. Lorenzo Bassi made a wide use of «incatenamenti apparenti e nascosti» (visible or hidden ties) to contain the thrust of arches and vaults, significantly called «motto espulsivo» (expulsive movement), and he foresaw hoops in the dome, stating that the dome «ben fabbricata, et ben coligata . . . haverà più motto o' sia gravezza all'ingiù concentrandosi meglio, che espulsivo o' al infori»[19] (the dome well constructed and encircled by hoops would will exert more vertical than horizontal forces), figure 8. In S. Alessandro the lack of adequate ties was considered one of the main reasons of the failure of the domed structure executed by Binago, and the reconstruction projects of the structure, proposed by Ricchino, show that an ample use of iron ties was foreseen at the extrados of the four main renewed arches to connect them better with the pillars, figure 9.

The debate regarding S. Lorenzo, moreover, brings to light the doubts that builders had in determining the size of a dome section and its curvature, and shows that they probably realised by intuition the existence of a relation between the section of the dome and its span. The supervisor of the yard, as a matter of fact, asked Bassi whether the thickness as few as «oncie 15 o 18» would have been adequate in relation to a dome

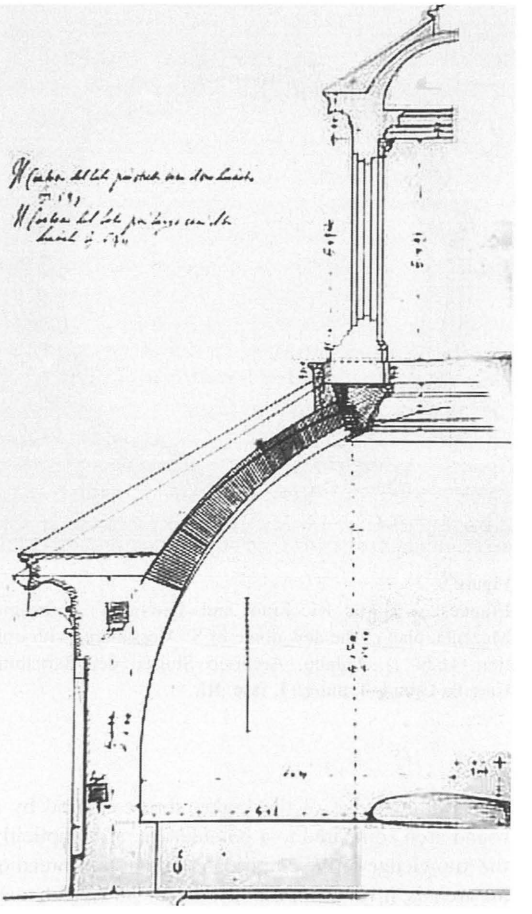


Figure 8
Francesco Maria Ricchino, partial cross section of the dome of S. Agostino in Milan with two wooden inner hoops (1614–18). Milano, Archivio Storico Civico, Raccolta Bianconi, IX, 24.

«di 40 braccia di diametro et alta alla proporzione».[20] Bassi was also asked to assert which kind of dome should have been better to build in relation to its geometry and building techniques. He was actually asked if it was preferable «fare la calotta di terzo acuto, di quarto acuto, mezzo tondo» (differently pointed) and « farla doppia o semplice» (double or simple), and the questions prove that the building culture was aware of the different behaviour of these types of dome.

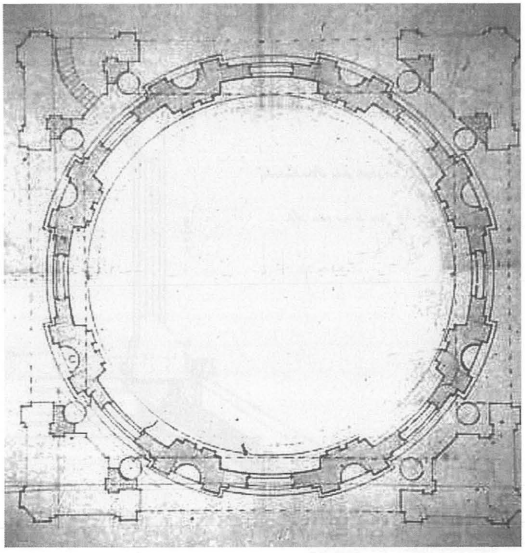


Figure 9
Francesco Maria Ricchino and Giovanni Ambrogio Mazenta, plan of the new dome of S. Alessandro, with iron ties (1629 ?). Milano, Archivio Storico dei Barnabiti, Cartella Grande I, mazzo I, fasc. III.

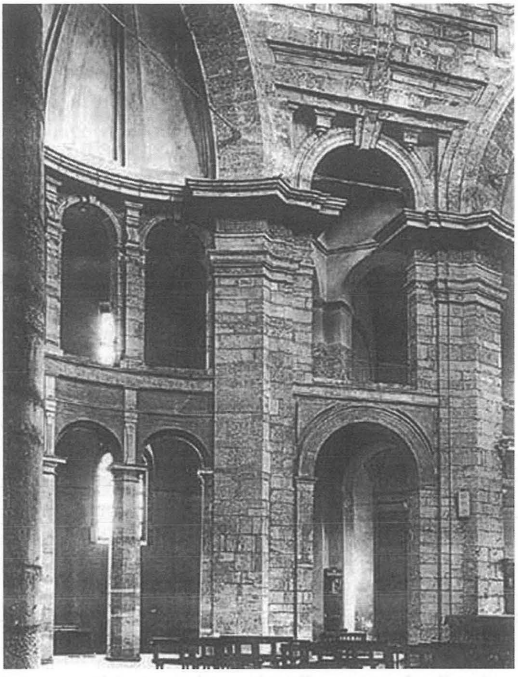


Figure 10
Inner view of S. Lorenzo, one of the tripartite pillars.

The knowledge of the higher thrust exerted by a round arch compared to a pointed one, and implicitly the knowledge of the empirical rule that the spread of an arch is inversely proportional to its height, was common sense at that time. Since the late XV century, when in Milan the semicircular arch begun to be preferred, domes were often planned with a round curvature but, probably because of their worse behaviour, they gained little success. For S. Lorenzo dome it was decided a fairly pointed curvature, figures 10–11, despite many projects had proposed a round one. The case of S. Alessandro dome is particularly interesting. The first dome —built by Binago with «tiburio» and resting on a drum, demolished a few months after the construction because worrying cracks had appeared— probably had a round curve. The new dome, planned by Ricchino in 1629–30, was extradoxed and rested on a drum, following the roman trends; nevertheless, the pointed profile of the dome, thought safer, would have not been visible, because it would have been covered by a wooden structure with semicircular

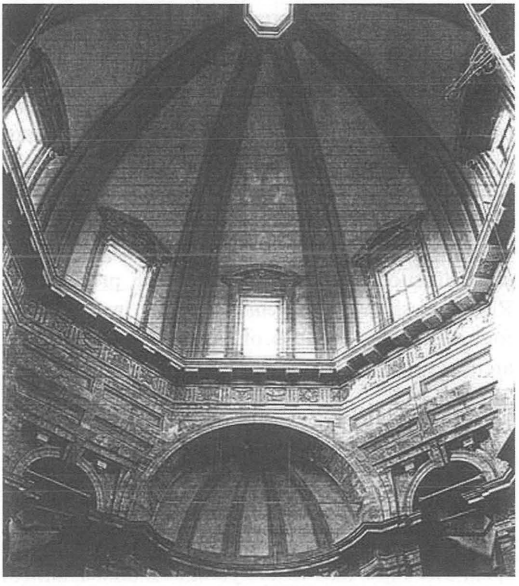


Figure 11
Inner view of the dome of S. Lorenzo.

profile that would have ennobled the external design of the dome, figure 6.

It is not improbable that even the long-lasting use of «tiburio» was justified, besides economical reasons, by the fact that most of the domes had a pointed profile. They were certainly considered safer but, since the birth of Renaissance, they were also considered barbarian, against the rules of antique architecture and therefore they had to be concealed. This problem may be testified by the superimposition of a «tiburio», around 1628, on the dome of S. Sebastiano, designed by Tibaldi with a pointed visible extrados.[21] As it is suggested by recent structural studies regarding S. Alessandro,[22] the superimposition of a «tiburio» particularly on domes whose impost is misaligned with the piers —just the case of domes resting on four free-standing pillars— does not seem to improve the performance of the domed structure. The «tiburio», in this case, though playing a stabilizing role of the 'orange slices' into which the dome typically breaks (Heyman, 1967), acts in a negative way on the whole dome structure. The «tiburio» may be considered, as a matter of fact, as an increase of the weight resting on the pillars, possibly causing an increase of their bending stress and tilt.

It is very difficult to find in archival documents some notice about the determination of the size of the piers in relation to their resistance to the tilts caused by the thrust of the vaults, but it does not seem that in the historical period here considered there were any widespread observed rules on this subject in Milan. Bassi and other architects in S. Lorenzo took into consideration the increase of the pillars section, transforming the original tripartite pillars into massive pillars with a triangular plan, but the changes were not executed. Binago, in S. Alessandro, seems to have observed a personal building criterium to guarantee the steadiness of the dome structure, suggesting to design the cathetus of the triangular pillars as long as a half of the span of the arches that joined the same pillars, figure 12. It is possible that Binago adopted this rule because he wanted to reproduce the proportions observed in the plan of the Bramante-Raffaello project for S. Peter in Rome, published by Serlio (1619, III, 64–65), but it seems more likely that he used this rule as a consequence of a misinterpretation of the first symmetry principle based on the first postulate of Archimedes, surely known in Milan during the first decades of the XVII century (Giustina, 2002).

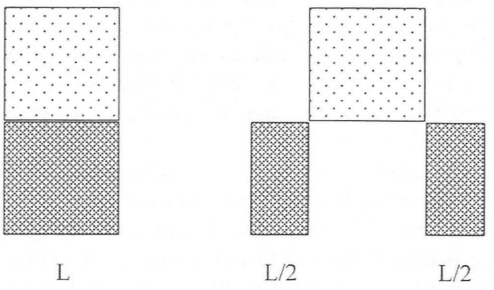


Figure 12
Scheme of Binago's rule of sizing the main pillars of S. Alessandro (author's).

The problem of the relation between the dome and the pillars was probably one of the most remarkable, because it involved the more general subject of the stability of the whole domed structural core. This relation was particularly critical in case of domes sustained by four free-standing pillars with the interposition of four main arches and pendentives.

Again, the debate on S. Lorenzo is very interesting. The dome firstly designed by Bassi was octagonal, pointed, partially extradoxed because of the presence of an external columned ring at the haunches.[23] The dome was connected to the tripartite pillars by four main round arches and four pendentives, which corresponded to the diagonal sides of the octagon and rested on minor arches connected to the pillars. The debate that arose on Bassi's plan in 1589–90 and the several different plans that were designed show that, besides the stylistic problems, the builders were very concerned with the domed core of the church. The supervisor of the yard asked Bassi whether it would be safe to rest the diagonal sides of the dome «sopra il vuoto dell'arco e fuori del dritto del pilastro»[24] (above pendentives resting on the void of an arch and misaligned with the pillars below).

A correct structural intuition, on which recent structural studies shed a first light,[25] made the builders fear that severe structural damages could be caused by the misalignment of dome impost with the piers. The different attempts at solving that problem can be easily seen through the plans, alternative to those of Bassi, proposed for S. Lorenzo. As a matter of fact, there were proposed projects in which the

octagonal dome rested on reinforced triangular pillars whose diagonal sides were prolonged up to the impost of the dome;[26] in this way the use of pendentives was avoided, as well as the misalignment between the impost of the dome and the pillars. Other plans[27] proposed circular domes resting, with arches and pendentives interposed, on triangular pillars, endowed with powerful free-standing twin columns along their diagonal sides. In this way, the pillars recalled those designed by Bramante for St. Peter in Rome (drawing Florence, Uffizi 20A) – and this was certainly one of the aims of the designers – but it should be noted that the twin columns, and in addition the doubling of the main four arches, were certainly introduced because they were supposed to help in reducing the problems given by the greater misalignment between the dome and the pillars.

The plans of a circular dome, proposed even by Bassi,[28] figure 13, were rejected and an octagonal dome was chosen. This kind of dome was probably supposed to give the structural core more guaranties of stability than a circular one, which was thought as a matter of fact, on the model of the Michelangelo's dome in St. Peter, « maggiormente in aria»[29] (more resting on empty).

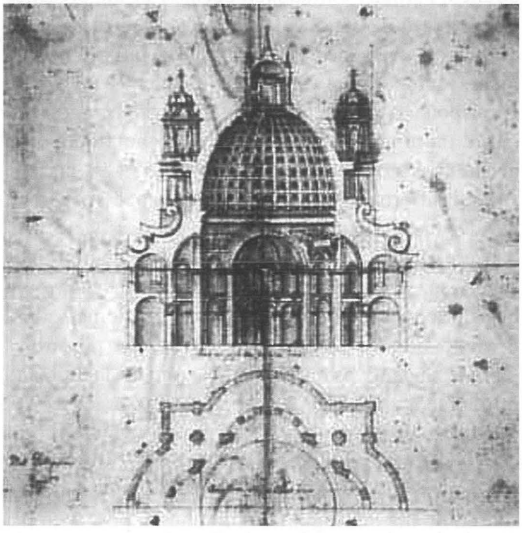


Figure 13
Martino Bassi, transverse cross section and partial ground plan of S. Lorenzo, unexecuted project. Milano, Archivio Storico Civico, Raccolta Bianconi, IV, 24.

Further complications to the relations between dome and free-standing pillars were also caused by the presence of a drum. Bassi does not seem to have foreseen a drum for S. Lorenzo dome, but many of the architects who proposed alternative plans did. The drum too did not belong to lombard architectural tradition and it begun to be considered (as in some plans for S. Lorenzo with a partially or an entirely extradoxed dome) or built (as, for example, in the domes of S. Vittore al Corpo, S. Fedele, S. Sebastiano designed in Milan by Tibaldi, or in the dome of S. Alessandro designed by Binago) wishing to follow the roman and the central Italian architectural trend. But, though solving the lighting problem, the interposition of a drum between the dome and the piers in case of free-standing pillars jointed by main arches, and particularly in presence of hemispherical domes, caused to the structure even greater problems.

As structural studies regarding S. Alessandro show,[30] the drum was actually exposed to the greatest strains at the base, in correspondence of the main arches, and at the same time, being an additional weight, possibly caused a dangerous increase of tension stress in the key stone of the arches leading them to collapse. This may have been one of the main reasons of the failure of Binago's dome, and even the archival documents seem to indicate that the largest cracks were mainly observed in the arches and in the base of the drum, while no mention to dome cracks was found (Giustina, 2002).

In conclusion, the problems examined in the present paper seem to show that the study of domes planned or build in Milan during the last decades of XVI and the first half of the XVII century has to be firstly related to the dialectic between the «tiburio» and the extradoxed dome, that is between lombard tradition and central Italy novelty.

The examination of this debate, and in particular the attempt of introducing up to date architectural trends, has allowed to shed a first light on construction practice and on builders' knowledge of the static behaviour of masonry domes.

As a result, this analysis, suggests that the study of domes can not be carried out, as too frequently happened, only considering aesthetic aspects or symbolic meanings, because, especially in presence of such challenging structures, formal choices were strongly conditioned, if not entirely determined, by the solutions given to structural problems.

Acknowledgements

The author acknowledges Prof. Stefano Della Torre and Silvia Corbetta of the I Faculty of Architecture, Politecnico di Milano and Prof. Ezio Giuriani, Prof. Francesco Genna, Prof. Paolo Riva, Dr. Elide Tomasoni, Dr. Alberto Arenghi of the Department of Civil Engineering, University of Brescia, for helpful discussions.

Notes

1. On widespread geometrical knowledge and rules, such as «Blondel's rule», see Mainstone (1968); Benvenuto (1981, 323–324); Heyman (1982, 59–62); Castellano, (1989); Di Pasquale (1996). See also the numerous suggestions about the determination of the size of the main elements of domed structures expressed by Vitruvius, and cited again, with some changes, in the treatises of the XVI century; see S. Serlio (1619, 202–220); Tibaldi (1590[I] ca.; 1988, 162–164). For this subject and for further references, see also Conforti, ed. (1997).
2. On the problems related to the determination of the size of the structures of Milan cathedral, see Ackerman (1991).
3. The church of S. Lorenzo belongs to the late IV century. It has a square, two storey double envelope plan with four apses, with a central dome supported by four pillars, each one composed by three smaller pillars joined by arches and vaults to form a nearly triangular pier. After the ruin of the original dome in 1573, Martino Bassi was called to reinforce the structures left behind and to build a new dome. Following the project approved in 1577 by the archbishop of Milan Carlo Borromeo, the works stopped when it was time to build the dome. The supervisor of the yard, Guido Mazenta, with the roman architect Tolomeo Rinaldi, doubted that the projected dome would be steady and in 1589–90 opened an ample debate that brought to the fulfilment of many different plans. Bassi's project was only partly modified and the dome was built within 1619. The dome, still existent, was octagonal, pointed shaped, with windows opened at the impost and with a partially visible extrados, hidden at the impost by a columned ring. On the debate, the proposals of new plans and the related bibliography, see Rocchi Coopmans de Yoldi (1991); Scotti (1999).
4. The church of S. Alessandro was begun in 1601 by the Barnabite monk Lorenzo Binago and it had a *quincunx* plan. The main central dome was built in 1625–1626 and it was probably hemispherical, covered by a «tiburio», and was superimposed on a drum with windows; it was joined to the four pillars below by four roman arches and four pendentives. The pillars had a triangular plan with two free-standing columns along the diagonal side. The dome was demolished in 1627 because serious cracks had appeared. After the reinforcement of the pillars and the arches, planned in 1629 by Fabio Mangone and executed probably by Francesco Maria Ricchino, it was planned a new dome, pointed and with entirely visible extrados, resting on a windowed drum. The plan, designed by Ricchino in 1629–1630, was not executed, and a new extradoxed dome was built in the second half of the XVII century by Giuseppe Quadrio. See Giustina, (2002); *Lorenzo Binago* (2002).
5. This situation lasted until the second half of the XVII century, when the building habits and the local skyline deeply changed because of the widespread use of the partially or entirely extradoxed dome, superimposed on a drum with windows.
6. Della Torre, Schofield (1994, 54–55). A previous interest for the model of the Pantheon in Milan can be found in the Scuole Canobiane, built after 1564, that were round and covered by a hemispherical dome near to that of the roman monument. Della Torre, Schofield (1994, 101, endnote 21).
7. On the dome of S. Sebastiano, see Rovetta (1990); D. Antonini (1998–99); A. Scotti, D. Antonini (2002).
8. Most of the documents regarding the structural discussion about S. Lorenzo dome (1589–90) can be found in the Biblioteca Ambrosiana, Milan, Raccolta Ferrari (BAM), Codex S 130 Sup.; for further references see Scotti (1999). For the documents concerning S. Alessandro, see Giustina (2002); *Lorenzo Binago* (2002).
9. BAM, S 130 Sup., CLXXXIV, M. Bassi.
10. BAM, S 130 Sup., CLXXV, M. Bassi.
11. BAM, S 130 Sup., CLXXV, M. Bassi.
12. Letter of L. Binago to the Deputati della Fabbrica del Duomo nuovo di Brescia, september 1615. See *Archivio* (1991, 410).
13. BAM, S 130 Sup., CLXXIV, M. Bassi. On this problem see Rocchi Coopmans de Yoldi (1991, 104–105).
14. BAM, S 130 Sup., CLXXVI, T. Rinaldi.
15. BAM, S 130 Sup., CLXXXIV, M. Bassi.
16. On the role played by experience in the understanding of arches and vaults behaviour, see Di Pasquale (1996).
17. BAM, S 130 Sup., CLXXXIV, M. Bassi.
18. L.B. Alberti (III, I) underlined that the strenght of masonry could be assured only by the absence of discontinuities.
19. BAM, S 130 Sup., CLXXXIV, M. Bassi.
20. BAM, S 130 Sup. CLXXIX, G. Mazenta. 1 braccio milanese = 0.595 m; 1 oncia = 0.049 m.
21. See Rovetta (1990); Antonini (1998–99); Scotti, Antonini (2002).

22. Arenghi, Tomasoni, Giustina (2002, to be published).
23. BAM, F 251 Inf., drawing n. 52. Scotti (1999, 130) observes that the drawing seems to be the one approved by archbishop Carlo Borromeo in 1577.
24. BAM, S 130 Sup., CLXXIX, G. Mazenta.
25. Arenghi, Tomasoni, Giustina (2002, to be published).
26. BAM, F 251 Inf., drawing n. 55, attribuited to Tolomeo Rinaldi. See Scotti (1999).
27. See for example the drawings: BAM, F 251 Inf., nn. 57–58; n. 56; n. 54; London, Victoria and Albert Museum, nn. 613, 614. See Rocchi Coopmans de Yoldi (1991); Scotti (1999).
28. Archivio Storico Civico di Milano, Raccolta Bianconi, IV, drawing n. 24.
29. BAM, S 130 Sup., CLXXXIV, M. Bassi.
30. Arenghi, Tomasoni, Giustina (2002, to be published).

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Antonio Ramos's Manuscript. Analysis of a scientific text with an empiric base

Juan Carlos Gómez de Cózar
Carmen Rodríguez Liñán
Filomena Pérez Gálvez

From the middle of the XVI century we find authors worried to find rules that allow get with guarantees elements of structures. The concept is not new, always empiric rules had been used. However, this gets importance when the proposed confirmation tools use mechanical concepts, then the empiric knowledge shares place with the scientist.

Inside the field that personally occupies us, the construction of vaults, the problem to solve was clear always. It was necessary to know as much as it pushes an arched construction on their supports, to be able to check if these dimensions were correctly.

Authors like La Hire, Belidor and Gautier expose their own theories and confirmation methods, more than enough well-known and even commented in the national editions previous of the association that it promotes this congress.

By the middle of the XVIII century, the figure of a Spanish architect, Antonio Ramos, that exposes its own method starting from the previous theories, compiled in a manuscript carried out by responsibility of the *Real Academia de Bellas Artes de San Fernando* appears.

To write about the manuscript as document is not the objective of this communication, so we will center in the interest and validity of the method of confirmation of supports that it proposes.

Content of the manuscript

The document that has arrived us is divided in seven notebooks. (Table 1).

After reading their reflections, we can reach the conclusion that the author proposes his method being based on two fundamental aspects: the knowledge of the theories and precedent methods and the observation of the reality.

Also, the curious of method is that it is really a confirmation method just as we understand the concept at the present time. It leaves of some dimensions proposed a priori (predimensions) for those that it uses an empiric formulation and later on it uses an analytic method that been worth or it corrects the proposed dimensions (calculation).

To deepen in their positions it is interesting to begin with the notebook nº 5 where is analyzed and they comment the methods of the previous authors:

> . . . del Sieur Gautier y Mr. Belidor que trataron del modo de encontrar los estribos de los arcos como en sus proposiciones se manifiestan y aunque dichos autores no han demostrado completamente lo que proponen, pues Gautier sólo demuestra la fuerza que hace una palanca curvada a buscar su natural, que es estar recta, lo que demuestra por triángulos semejantes, sin hacerse el cargo del peralte de su dovela ni de sus divisiones, ni da elevación alguna al pie derecho, circunstancias muy precisas en todo género de arcos y bóvedas.
>
> Mr. Bélidor está más extenso y da espesor a las dovelas, hace su división y se hace cargo del pie derecho;

Table 1. Content of the notebooks of the Antonio Ramos's manuscript

Notebook nº	Content
1	1ª Cuánta potencia o impulso se necesita para volcar un pie derecho, pilar o muro en cualquier punto de él en que se haga el empuje.
	2ª Cuánto gravita cada volsor o dovela de un arco contra el pie derecho o pilar que lo sostiene.
2	Parte II De las propiedades del medio arco y su pie derecho.
3	(Por la muerte del autor, quedó sin ordenar)
4	(Operaciones prácticas)
5	En gracia de los que no hayan estudiado esta doctrina de las proporciones parte esencial de la Aritmética que suponemos.
6	En limpio.
7	Primer borrador.
Figuras	Cuaderno de figuras (incompleto)

pero no da razón de sus operaciones por demostración, como se puede ver en sus proposiciones . . .

. . . y aunque los dos expresados autores no perfeccionaron los expresados problemas no puedo dejar de loarlos . . .

Once centered the problem, translates to Bélidor in the exhibition of the previously exposed method, and the following conclusions where it describes the mechanism of break of an arch settles down (perfectly defined):

. . . Según la experiencia nos enseña, el medio arco y su pilar son un pie derecho, y si se mueve es sobre su hipomoclio.

2° Si el medio arco tiene más potencia que resistencia, el pie derecho se siente en las juntas de su clave siguiendo la fracción casi perpendicular.

3° Y si la escasez del estribo es mucha, se siente en los tercios y se desploma el pie derecho hacia la parte exterior del hueco del arco, moviéndose unido el pie derecho con los volsores que están sobre su imposta hasta la mitad del medio arco o cuadrante.

4° El resto de volsores hasta la clave se desprenden hacia el centro del arco casi unidos, variando de sentir sus juntas, pues la fuerza de la frasión del tercio siempre se queda más ancha en la bocilla inferior del arco que la superior, y la fracción de la junta hacia arriba sigue casi perpendicular.

Theoretical foundations

Although in the notebooks 6° and 7° it outlines the same problems again, it is in the notebooks 1𝕀 and 2𝕀 where the author proposes his analysis method. In the first notebook he/she tries to obtain:

Cuánta potencia o impulso se necesita para volcar un pie derecho, pilar o muro en cualquier punto de él en que se haga el empuje.

To solve the problem, it assimilates the stirrups to a lever, defining it as:

un cuerpo largo e inflexible que de tal modo descansa y se afianza sobre un punto, que sólo puede moverse alrededor de él como si fuera su centro.

In the figure 1, their propositions can be appreciated, as for the laws of the lever and their peculiar form of trying to the angular levers.

In fact, it tries to the support as levers of 2° order, in those that the resistance is located among the *hipomoclio* (turn point) and the power. In this type of levers, the product of the power or resistance for their respective distances to the *hipomoclio* should be identical so that the lever is in balance.

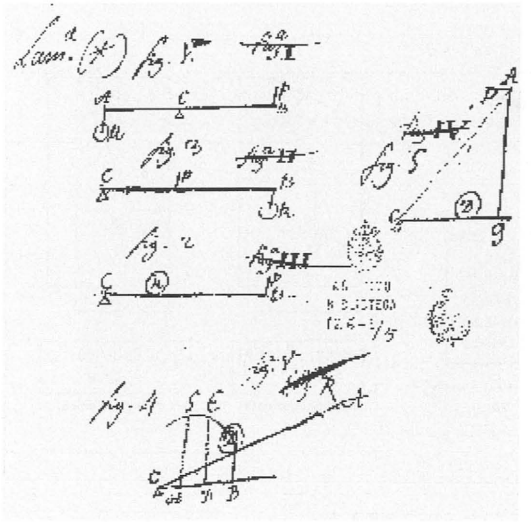


Figure 1

The figure 1 that represents to a sheet without to classify contained in the notebook nº 6, develops different types of levers. Inside this sheet, the figures 2, 4 and 5 contain levers of 2º order.

To solve the fundamental problem it uses the figure V of the sheet IV (fig. 2). Once he obtains the maximum power that is necessary for the balance, when this forms right angle with the horizontal one, he obtains that fraction of this gets lost when it acts with a certain inclination. To establish this relationship, it proposes the following thing (proposition 4ª, notebook 1º):

> Si un pie derecho es oprimido por una potencia verticalmente, su resistencia será según el ángulo que causa la dirección vertical con la perpendicular de la línea o columna de dirección que pasa por el centro de gravedad.

In the figure 3 the problem has been represented. In the left part of the figure it is observed like it is necessary to increase the value of the power (P ') so that the balance takes place between power and resistance (the resultant of both actions goes by the *hipomoclio*). In the right part it is obtained as much as he decreases the value of the power in function of the angle that forms with the vertical one.

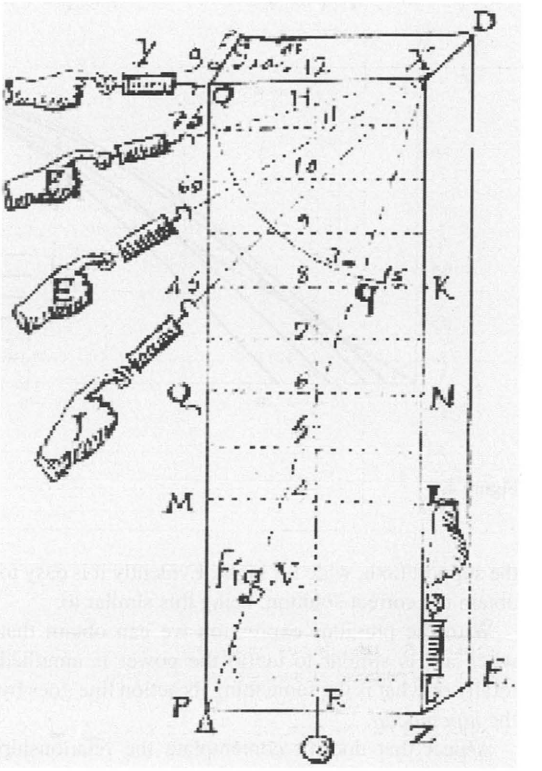


Figure 2

As A. Ramos settles down this relationship is similar to:

Relationship that becomes an acceptable approach to the correct solution in function of the proportions of

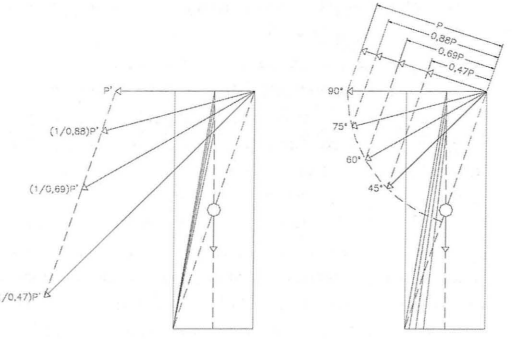


Figure 3

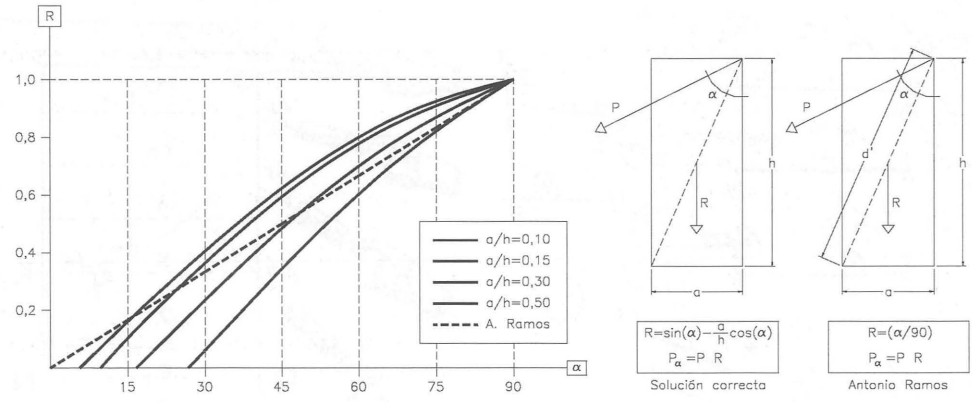


Figure 4

the support (axh, wide for high). Evidently it is easy to obtain the correct solution, being this similar to:

With the previous expression we can obtain that when a/h is similar to tan(á) the power is annulled totally or what is the same thing its action line goes by the *hipomoclio*.

Aspect that doesn't contemplate the relationship that A. Ramos settles down.

In the figure 4 the comparison has been represented among the relationship settled down by the author of the manuscript and the real solution for different proportions of the support.

In the table 2 the values of the powers are exposed that are obtained of the previous comparison, and the error percentage that A. Ramos makes.

We observe like it stops proportions between the interval 0,2–0,3 and angles non superiors at 30º, the error that is made (13%) it is perfectly acceptable.

Proposed method

After this interesting preamble, in the notebook 2º, it is the fundamental aspect of the manuscript that is:

> Cuánto gravita cada volsor o dovela de un arco contra el pie derecho o pilar que lo sostiene.

The notebook 2º begins this way:

Table 2. Comparation between real solution and A. Ramos propositions

α	a/h = 0,1			a/h = 0,2			a/h = 0,3			a/h = 0,4		
	Real	Ramos	% Error	Real	Ramos	% Error	Real	Ramos	% Error	Real	Ramos	% Error
15	3486	3582	273	5560	14120	15393		31033			53480	
30	8885	7164	1936	27686	28240	200	44724	62067	3877	49284	106960	11702
45	13677	10746	2143	47926	42361	1161	92165	93100	101	136138	160440	1785
60	17538	14328	1830	64899	56481	1297	133325	124134	689	213715	213921	9
75	20204	17910	1135	77449	70601	884	165399	155167	618	276727	267401	337
90	21492	21492	0	84722	84722	0	186201	186201	0	320881	320881	0

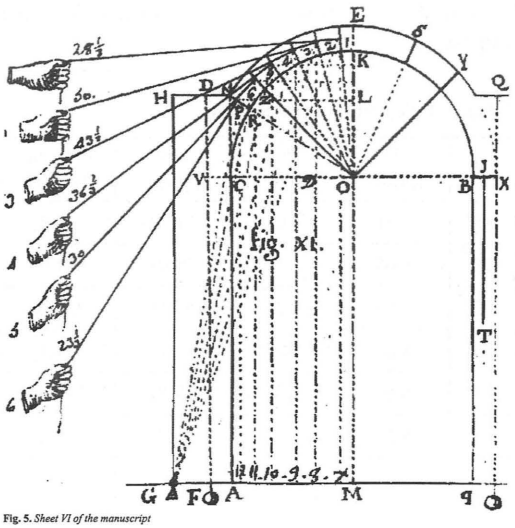


Fig. 5. *Sheet VI of the manuscript*

Figure 5
Sheet VI of the manuscript

Antes de entrar en la demostración de los arcos y de como hacen su empuje contra su pie derecho ya sean semicirculares, escarzanos, elípticos, a cordel, o de la forma que sean, y lo mismo en todo género de bóvedas de cañón, es menester prevenir que guardan unas mismas propiedades, esto es que el *medio arco y su pie derecho se ha de considerar todo él compuesto como un solo pie derecho.*

. . .

Luego el medio arco y el pie derecho tendrán las mismas proporciones que se han demostrado en la primera parte hablando de los pies derechos: esto es que la resistencia del pie derecho será según fuese la distancia que hay del hipomoclio G al punto F que es por donde pasa la línea de dirección FD que pasa por el centro de gravedad dividiendo la superficie del pie derecho y arco en dos partes iguales por ser el compuesto un sólo pie derecho ACZKEMHG.

The figure 5 that reproduces to the sheet VI of the manuscript it contains the confirmation model that will use in the calculations.

It is in the sheet VII (figure 6) the one that will use to carry out the confirmation of the fundamental proposition of this notebook (proposition I, notebook 2°):

Digo que los volsores no emplean más esfuerzo contra su pie derecho o volsor inmediato , que el ángulo que forma la línea perpendicular que sale de su junta y termina en la columna, o la línea de dirección que pasa por el centro de gravedad del arco y pie derecho, la que se supone perpendicular al horizonte HX.

The rest of propositions contained in the notebook is devoted to obtain the different surfaces and distances that he needs to carry out the main demonstration that is that the support has enough dimension to resist the push of the arch. Therefore the previous paragraph, contains its fundamental theory, already exposed in the previous chapter:

Cada *volsor* (dovela) plantea su esfuerzo en función del ángulo que forma la perpendicular a su plano de asiento.

According to the above-mentioned, if each dovela has a weight (P) and its action line (always) vertical) it forms a certain angle with the meeting with regard to the following one, if it is considered an entire single right foot, the fraction of power that makes

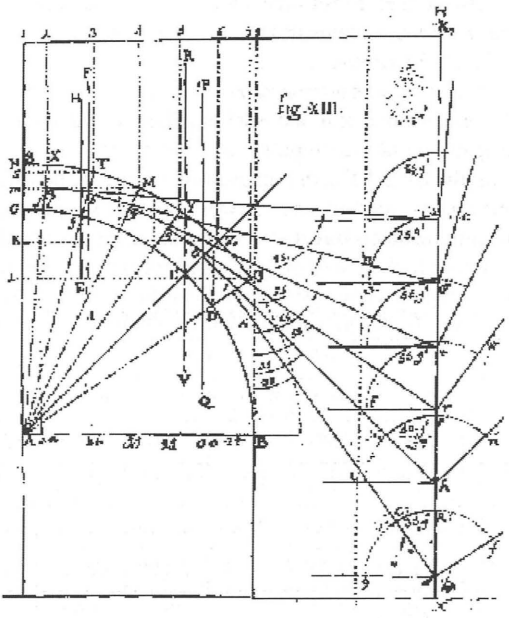


Figure 6
Sheet VII (Fig. XIII) of manuscript

action it is obtained according to the angle, just as he/she settled down in the first notebook.

Once obtained this fraction of power for each one of the dovelas, starting from their distance until the hipomoclio, the overturn action is obtained that the arch or vault is carrying out on the right foot (pillar or wall more semiarco).

Use of an empiric formula

Once defined the confirmation method, from a practical point of view, is necessary to carry out a predimensionated of the element to check. The formula that utliza A. Ramos are the following one:

$$e = \frac{1}{2}\sqrt{h + l + r + S + P}$$

Where:

e = wide of the looked for support
h = height of the support
l = height of the vault
r = radius of the vault
S = surface of the half-arch
P = power of the half-arch (calculated according to their method).

The formula gets the attention because it mixes magnitudes of different dimensions (lineal and superficial). The most interesting thing is that it introduces adding the power of the semiarco, magnitude that is directly proportional to the push and therefore to the width of the looked for support. From this point of view, the formula can be used for any arch type (reduced, semicircular or pointed).

Evaluation of the method

As it is observed starting from their positions (forces perpendicular to the joints, each piece of arch contributes a certain fraction of the push, the whole group it constitutes an only support and application of the rules of the lever) the method is an approach to the problem.

To evaluate the approach degree that A. Ramos gets, in the following table their calculations have been re-done, starting from the formulation that proposes:

Table 3. Calculations of A. Ramos

α	P (pies2)	Pot (pies2)	Dist (pies)	Momento (pies3)
85°	4.31	4.07	57.34	233.38
75°	8.63	7.19	55.91	401.99
65°	8.63	6.23	54.16	337.43
55°	8.63	5.27	52.12	274.7
45°	8.63	4.31	49.82	214.74
35°	8.63	3.35	47.3	158.46
Total:				1620.7

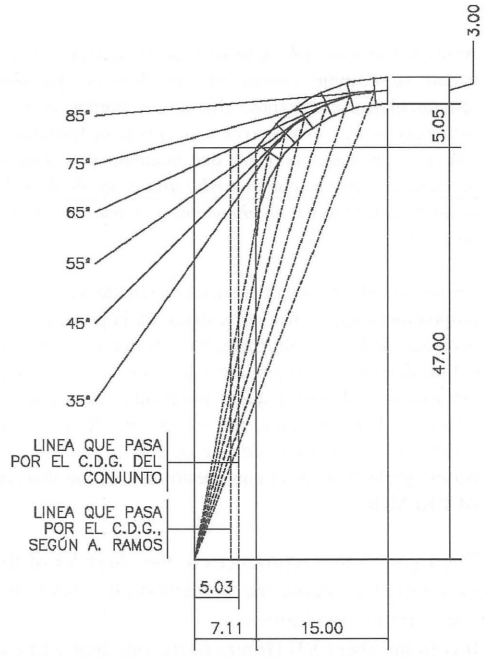


Figure 7
Model based on the figure XI of the sheet VI of the manuscript

The figure 7 includes the dimensions that he uses. In the previous table, (α) it is the angle that forms each joint with the vertical one, (P) it is the weight of each one of the piece of arch, (Pot) it is the power of each one obtained in function of the angle of the joint and (Dist) it is the distance from the center of each joint until the *hipomoclio*. In function of the previous results, a total moment of 1620,70 pies3, is obtained that corresponds to a resistance of 322,22 pies2. As the group denominated support possesses 391,06 pies2 of resistance, the dimention is correct.

Certainly, the part more difficult of accepting of their theories it is the corresponding to the obtaining of the value of the push that although he is not him in an explicit way he obtains it like successive sum starting from the load of the piece of arch and of their inclination of joints. From our current optics we know that the push is the horizontal component from the stress to which are subjected the different piece of arch that in a case as this in the one that the actions are all vertical ones has an unique value for the whole arch. From this position, using the total moment that A. Ramos obtains, we can obtain the value of the push (H) just as we understand it today in day to see in that field of variability moves.

The figure 8 represents the problem. The moment calculated by A. Ramoss are equal to (H × h).

Making the previous operation obtains that for h = 53,55 feet, H = 30,26 pies2.

Therefore the relationship that is obtained among the push H and the vertical load of the half- arch (H/V) it is similar to 0,63 that it is quite acceptable.

As we see, for the type of arch used and for the proportions of the used support (a/h = 0,15), the method fits sufficiently. However, for another type of arches, mainly reduced, we can sense as their application it won't be so correct since obtaining the push starting from the load fraction in function of the angle of the joints, difficultly relationships will be obtained (H/V) superiors to the unit that are characteristic in very reduced arches. The figure 9 analyzes the problem.

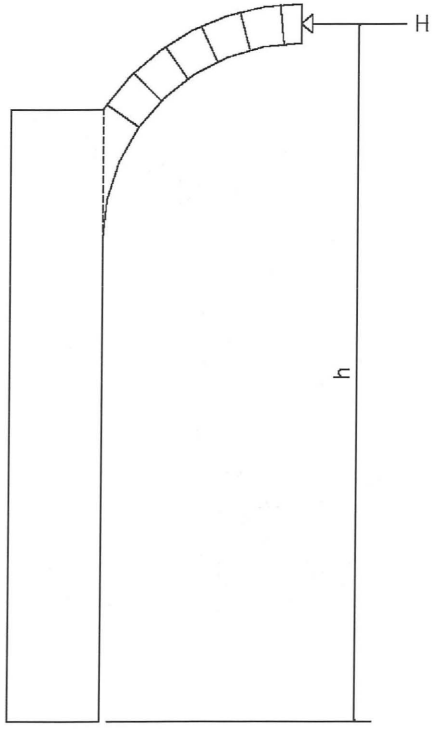


Figure 8
Real push (H) in an arch or vault

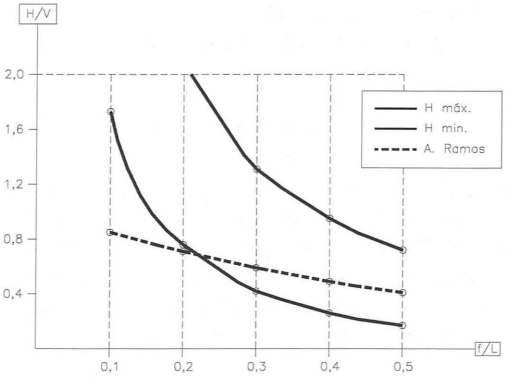


Figure 9
Relationship between the pushes (H/V) according to A. Ramos and the maximum or minimum real for diferent relations (f/L; high/span) of archs

The results are conclusive. For relationships (f/L) inferior at 0,20 the method is not valid, however for superior proportions up to 0,50 (semicircular arch) the obtained results are very satisfactory.

Conclusions

This Spanish contribution continues in the line of methods that only check the dimensions of the contention elements and they don't lend, still, attention to determine the stability of the arch in function of its geometry and thickness. Fact that is demonstrated by the use of normal directions to the joints like actions carried out on the support and not how distribution of stress inside the arch or vault.

However, the use of an empiric formula for predimensior the structure transforms to the work method into a compact tool for diverse geometries of arches, with a degree of sufficiently high success, just as we has been proven.

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Supplying of masonry materials in the construction of the crypt of Santa María la Real de la Almudena, Madrid, Spain, 1883–1911

M. Gómez Heras
R. Fort González

The importance of the petrological and petrophysical studies of stony materials used on architecture is progressively gaining importance, both for the construction of new buildings, and for the restoration and rehabilitation of historical buildings. This work presents an example of the petrophysical studies that were carried out for the selection of the most suitable lithologies for the construction of the crypt of *Santa María la Real de la Almudena* Cathedral (Madrid) in the second half of the 19th century. It is also shown how, due to different causes, the type of materials used throughout the construction of the Crypt was changed. These changes affected the construction, both delaying it and resulting in a building made up with several different materials. This confirms a tendency that is very often observed on historical buildings where construction was developed during a long period of time. It is in these cases where it is especially important to carry out a detailed documentary analysis of the factors causing this variability.

The importance of this analysis mainly lies on two points. On one hand, it can reveal important historical details concerning the interpretation of the building. On the other hand, it gives us information about the quarries from where the original materials were extracted, allowing us to obtain stones of exactly the same characteristics as those once employed in order to make substitutions of architectonic elements. In that way, this work shows how the combination of both documentary and geological data can be an important approach in order to understand many subjects dealing with the history of architecture.

Introduction

The origin of materials used on a building and how it affects its construction is an interesting subject in the study of any building. The origin and transformation processes of the materials used offers us historical, socio-economical and industrial data on one of the oldest human activities: the quarrying and use of stone resources.

The determination of original quarries for a building allows for optimal restoration when material has been lost or needs to be substituted. That is an important fact because there are not only changes between stone types but there are also changes between different quarries of the same lithology. These changes could cause incompatibilities between new and original materials.

The present work mainly has two aims. First, it reveals the process of selection and the supplying history of the stone in the Crypt of the Cathedral of the Almudena (Cathedral of Madrid). Second, the study of the documentation is completed with some petrological data which allow us locate the quarries used in this building.

The Crypt has been selected because it was built with uncommon stony materials in the city of Madrid. The traditional architecture in Madrid has been made

with stone, both granite from Sierra de Guadarrama and limestone from Colmenar de Oreja, as well as clay bricks. Many of the buildings from the 17th to the beginning of 19th century have been built with those materials (Dapena et al. 1988). At the end of 19th century new materials began to be used, mainly because of the facilities introduced by the new ways of transport. The stone called Piedra de Novelda was one of the most often used (Fort et al. 2002).

The exhaustive selection process of the stone that included some petrophysical tests was another reason for the choosing selection of the building. Furthermore, since the Crypt is part of the Cathedral we can compare some aspects with the Fabric in the cathedrals of the previous centuries.

Methodology

The present work mainly deals with showing the results obtained in the documented sources of the building to determine the history of the supplying of the stony material. From this historical data the possible origin of the stony materials used in this building work has been established. Petrographical and petrophysical tests of samples from the building and quarries have been made to support the historical data obtained from the documents.

The location of the original quarries of the materials used in any element of architectural heritage should follow the methodology summarised in the chart of figure 1.

Origin of the Construction of the Cathedral of the Almudena

The idea of building a large church in Madrid with a name of the Virgin Mary began when the dogma of Immaculate Conception was proclaimed in 1854. The Spanish people were very influential in the proclamation of this dogma and this church was destined to be the largest sanctuary of the Virgin in Spain.

The name Santa María de la Almudena has its origin in the Arab word *al-mudaina* that means *the citadel* because Alfonso VI discovered an image of the Virgin in the city walls after the conquering of Madrid in 1085.

After the revolution of September of 1868 it was decided to demolish the old temple of Santa María de la Almudena to make the streets of Bailén and Mayor

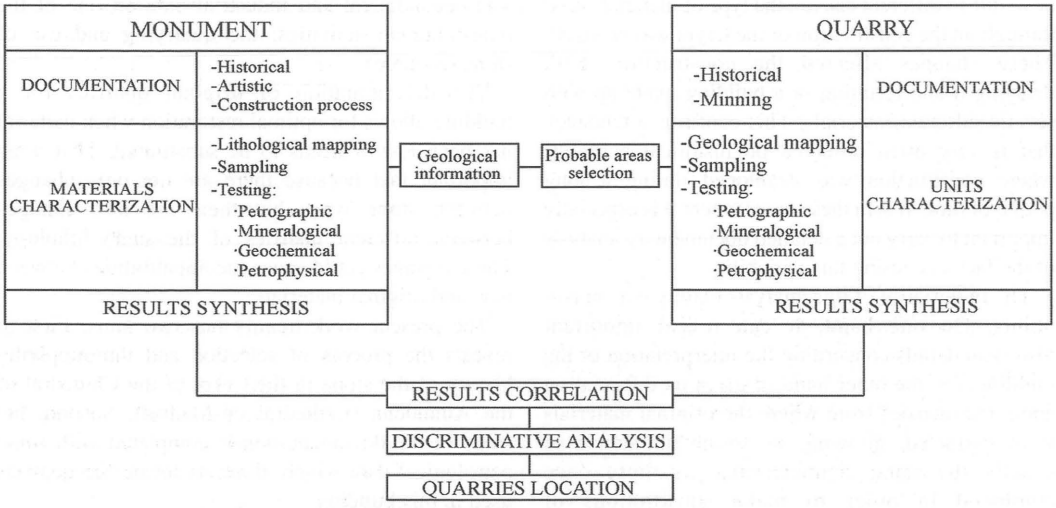


Figure 1
Methodological synthesis on the location of original quarries of stony material in the historical-artistic heritage (after Fort 1996).

wider moving the worship to the Church of the Santísimo Sacramento (now the military church). That church of Santa María was placed in the north corner of the present crossroad of Bailén and Mayor streets, probably in the place where an old mosque stood.

The Queen María de las Mercedes wished to help the Archbrotherhood of the Almudena and devouts in the construction of a new church. As the result, in conjunction with the demolition of the old church, it was decided to build a big temple under the name of Santa Maria la Real de la Almudena in the plot given by the King Alfonso XII. The king also built the temple as a mausoleum to his deceased wife.

In 1878 the Marques de Cubas was appointed as architect of the building work. The first studies of the plot were started in 1881 and on 4 April 1883 the *foundation stone* was laid. This temple under construction was to become the future Cathedral of the Diocese of Madrid-Alcalá erected by Leon XIII in 1884. As a result, the Marques de Cubas transformed the previous parish church project into a new one.

The Cathedral of the Almudena has had several stages in its construction from 1883. The first stage includes the construction of the crypt that lasted from 1883 to 1911. The responsible architects during this stage were the Marques de Cubas, until his death in 1899, Miguel de Olavaria, who died in 1904, and Enrique Repullés y Vargas. The second stage overlapped with the first and extended from 1910, when the first pillar of the cathedral was set, to 1944, when an announcement was made for a new contest to change the project (this stage includes the interruption of the Spanish Civil War). After the death of Repullés two architects followed: Juan Moya until 1936 and Luis Mosteiro from 1939. The third stage, following the new project of Fernando Chueca-Goitia and Carlos Sidro, lasted from 1950 to 1965. The work was then stopped until 1988 (except for a short period of work in 1969). The last stage extended from 1988 to 1993 when the church was consecrated. The work, including the inner decoration and some architectural elements, continues from 1993 to the present day.



Figure 2
General view of the Crypt of the Cathedral of Santa Maria de la Almudena

The original project of Marques de Cubas consisted of a neorromanesque crypt and a neogothic church. This study refers to the materials used in the construction of the crypt (1883–1911) which is the only finished part of the building according to his project.

The Documented Sources of the Cathedral

The Fabric of a cathedral was one of the administrations of the Chapter economy. This budget was looked after by one of the canons that received different names in the Spanish Cathedrals: *Obrero*, *Fabriquero* or *Mayordomo de Fábrica* (López-Arévalo 1966; Torroja 1977; Cortón 1990; Galera 1982).

The Fabric includes not only the construction but also all things related to the conservation and improvement of the building. The costs of candles, oil or decorations for feast days were also the responsibility of the Fabric. All financial transactions had to be accounted for in the *Fabric Rolls.*

All the monetary deposits of the Fabric came from several sources. There were cases in which this documentation was not included in the Fabric Rolls; rather it was spread throughout several cathedral books. In other cases, like that of the Cathedral of Oviedo, Fabric Rolls were missing (Caso 1981). Finally, it should be noted that other cathedrals have registers that are not continuous.

Other important documents for the study of the Fabric of a Cathedral are the Chapter minutes. On some occasions these are the only available

documents. The work of the Fabric Canon was supervised by the Chapter and that work is often noted in the minutes, also known as the Chapter Acts.

The case of the Cathedral of Almudena is very different for two reasons. On one hand, the power and deposit capacity of the Catholic Church decreased during the 18th and 19th centuries because of the coming of the Bourbons and the Enlightenment. In Spain the culmination of this process was the expropriations (i.e. Desamortizaciones) of the 19th century until the treaty with the Holy See in 1851. As a result, the governing bodies of the Church, especially the local ones like the chapters of the cathedrals, relinquished their authority and financial capacity. Therefore the economy of the cathedrals was simplified and a new concept of Chapter was established. This new concept was a major factor in the creation of the new Chapter of the Cathedral of Madrid-Alcalá.

On the other hand, this building was not designed as a cathedral from the first moment. The project of the building was made when Madrid was obligated to the diocese of Toledo. Therefore, the structure of the documentation since the beginning of the building was not common for a cathedral church.

The documentation used for the purpose of this work comprised the 1879–1911 period of the first book of minutes of the building's board meetings known as the *Libro de actas de la Junta de Edificación del Templo de Santa María de la Almudena*. This book is kept in the historical archive of the diocese of Madrid. That documentation is complemented with dozens of folders including several books of accounts and minutes. Many of those books are not well studied and are now in inventory.

The first book of the building board meeting minutes began with the initial session on 29 June 1879 and finished after the session on 29 December 1934. At the end there is a note from the secretary informing that the book was stolen during the Spanish Civil War and was later recovered.

The *Building Board* was established by the order of the Cardinal Archbishop of Toledo. In the first board session the Cardinal was named as president, Mr Julián de Pando, court visitor, as vice-president, the Marques de Montalvo as treasurer, Mr Francisco de Cubas as the chief architect and Mr. Manuel Calderón Sánchez, economist priest of the parish of Santa María de la Almudena, as secretary.

This board was mainly secular, unlike the chapters of the old cathedrals. The secretary was the only clergy in addition to the Archbishop. This board remained after the new diocese of Madrid-Alcalá was erected. We would expect that after this change, the chapter would look after the building works, but this was not the case. The Bishop of Madrid-Alcalá was named president instead of the Bishop of Toledo. Moreover, the Dean did not belong to the Building Board until 1899. The chapter was not often mentioned. The chapter was obligated to the Building Board and all building related matters had to be accepted by the Board. For example, in the session of 15 November 1909, the Bishop had to ask for permission to move the chapter to the crypt. In addition to the Building Board, the *Executive Commission on the Construction of the Cathedral Temple of Nuestra Señora de la Almudena* was created in 1909. The Commission had its own minutes book that was kept in the historical archive of the diocese.

Process of Selection of the Building Stone

The selection process began in 1885 but there are also some previous references to stone types dating back to 1883. That process is one of the most interesting points about the origin of the stony material. The responsible architect, Marques de Cubas, wanted a correct selection of stone instead of the main tendency in the Middle Ages when the selection of the nearest and softest stone was more important than the most lasting[1] (Cubas 1886).

Therefore, the course of the selection of stone was made with careful thoroughness. The first selection process lasted from 7 February 1885, when the first proposals was taken, until 27 September 1887 when the building board finally chose one of the stone types. This process included twenty-three stone types from many points of Spain and some foreign locations.

The first proposed lithologies for the construction were White Marble from Cáceres and dolostone from Uclés (Cuenca) both offered by the same contractor (7 Feb. 1885).[2] These stones had not been often used in Madrid, so the Building Board ordered Mr. de Salces, auxiliary architect, to perform inspections of the marble quarries and the conservation state of the

Monastery of Uclés which was made with the dolostone. That is a very interesting point for the field of the Geology applied to the study of heritage.[3]

Proposals of other stones were also noted in the minutes: Limestone from Baides (Guadalajara), Limestone from Elda (Alicante) and Marble from Alconera (Badajoz). There was a contest with these proposals and many others received as a result of an announcement placed in newspapers. Twenty-three stone types were initially selected. These stone types were tested using arch calculations in the school of civil engineers (9 Jan. 1886).

Marques de Cubas presented a report dealing with the most suitable stones in the Building Board meeting on 9 January 1886. This report was published entirely in the Bishop Bulletin and included the results of the tests for the twenty-three types of stone (figure 3). From these results five stone types were chosen for further tests: white and grey marble from Alconera, limestone from Alhama de Aragón (Zaragoza), Limestone from Baides and Limestone from Uclés. A commission of architects was summoned for the final decision (6 Oct. 1886). This commission was formed by Mr. José María Aguilar and Mr. Joaquín de la Concha y Alcalde and concluded that all the types of stone would be valid so the cheapest and more abundant would have to be chosen. It was decided to choose the stones from Baides and Alhama (26 Oct. 1886).

The Alhama stones delivered did not have the same characteristics as the tested blocks and they possessed oxide veins that did not make it suitable. The stone coming from Baides was selected to begin the building work since the stone from Alhama was rejected (3 Feb.; 27 Sep. 1887). However, this would not be the definitive material.

There were three main ways in which the stone was supplied to cathedrals: exploitation of quarries belonging to the Chapter, exploitation by quarry workers who sold to businesses related with masonry, and contracts with quarry workers who would exploit their own stone. The first two options had been used since at least the 13th century. The first way was predominant in cathedrals like Oviedo and Toledo, but in more modern ones like Segovia contractual relationships were common (Cortón 1990).

The Cathedral of the Almudena was chosen to contract with quarry workers. This fact produced serious troubles in the supplying of the material during the first years mainly due to problems with quarry contractor. This delayed the setting of the masonry stones because the contractor assured that there would be difficulty extracting the material in the terms of the contract. However, Marques de Cubas stated that he knew that other building works did not experience any difficulty. These kinds of troubles led the board to attempt to own the quarries () and finally to void the contract with those quarries (4 Apr. 1888; 7 Nov. 1888).

A new contest was created to choose a new stony material to continue with the building work. The following localities were proposed: Almería, Petrel, Estepa, Viana de Jadraque (Vianilla, sic) and Portugal (10 Dec. 1888). The stone coming from Viana de Jadraque (Guadalajara) was quickly selected because it was very similar to that coming from Baides.[4] Since there was not a contract with Viana de Jadraque, the contest was abolished (3 Apr. 1889). Soon after, an agreement was reached with an English society established in Porto called Murat & Company. The company supplied stones that came from Portugal, although the minutes do not reveal the specific locality.

In the meeting of 14 January 1892, the Building Board talked about negotiations made to get softer stones to do the decorations on chapitels and carved arches. The following were proposed: Petrel, Campanil and Portugal[5] but there is no mention about the final decision.

The period from 1892 to 1900 was characterized for new troubles between quarries and the Building Board. In 1892 Porto stone increased its price because of the rise in customs taxes and there was not an agreement about the new costs of the stones (24 Feb. 1892). Apart from that there was a large worker strike in the quarry of Portugal (23 Oct. 1897). Also, the building work became slower because on 2 February 1899 the director architect Marqués de Cubas died. Therefore in 1900 contractors of Porto threatened to void the contract if a minimum order of 100 m^3 per month was not completed in six months as was specifically stated in the contract (15 Jun. 1900). This did not occur because the Board refunded the deposit that was made by the contractors to guarantee the supplying of the minimum order. As a result, the Board was exempted of making the minimum order.

In 1904, the result of what stone would be used for the main building was awarded after the tests were

Clases de Piedra y su procedencia	Peso de un metro cúbico (Kilogs.)	Peso de un pie cúbico (Kilogs.)	Lado de los cubos de ensayo (Cts.)	Carga de prueba (Kilogs.)	Carga de rotura por centímetro cuadrado (Kilogs.)	Observaciones
Granítica berroqueña del Berrocal (Madrid)	2.681	58	6	17.596	489	Se rajó el cubo con la carga de prueba
Marmórea azulada (Alconera, Badajoz)	2.769	59'90	6	17.236	479	Idem.
Mármol Rabaggiore Corraza (Italia)	3.020	65'33	5	10.664	427	Idem.
Mármol Rojo Renteríe (Guipúzcoa)	3.016	65'24	5	9.976	399	Idem.
Mármol violáceo (Granada)	2.972	64'28	5	9.912	397	Idem.
Mármol rosáceo Alhama (Aragón)	2.620	66'67	6	12.576	344	Idem.
Mármol blanco Macad (sic) (Almería)	3.016	65'24	5	8.600	344	Idem.
Calcárea oscura Baides (Guadalajara)	2.591	56	6	11.864	329	Idem.
Calcárea blanca Colmenar de Oreja (Madrid)	2.599	56'22	6	11.494	319	Idem.
Calcárea Petrel (Alicante)	2.300	49'75	5	5.230	276	Peso y resistencia término medio
			6	12.232	276	Idem.
Calcárea Morena Tafalla (Navarra)	2.588	55'98	6	9.444	262	Idem.
Mármol Vordiglio (Italia)	2.920	63'16	5	6.040	242	Idem.
Calcárea blanca Monóvar (Alicante)	2.204	47'59	5	6.040	242	Idem.
Calcárea blanca Novelda	2.300	49'75	5	3.640	135	Idem.
			6	4.440	135	Idem.
Calcárea morena Lamorqui, (sic) (Alicante)	2.281	49'34	5	3.080	134	Idem.
			6	5.240	134	Idem.
Calcárea blanca Tudela (Navarra)	2.030	43'91	6	4.440	123	Idem.
Calcárea morena Roda ó Bará (Tarragona)	2.009	43'43	6	4.200	117	Idem.
Calcárea blanca Arcos (Cuenca)	1.813	39'22	6	4.200	117	Id. usada en la Catedral de Cuenca
Calcárea blanca Sax (Alicante)	2.093	45'27	6	3.640	101	Idem.
Calcárea blanca Fonz (Huesca)	2.280	49'32	5	1.960	78	Se aplastó reduciéndose a polvo en la prueba
Calcárea blanca (Segovia)	1.896	41'01	5	1.800	64	Id. resistencia y peso término medio
			6	1.992	64	
Calcárea amarillenta Uclés (Cuenca)	1.847	39'95	6	2.040	57	Idem.
Calcárea blanca Luna (Zaragoza)	1.907	41'25	6	1.992	55	Idem.

Figure 3
Table with the results of the tests according to the original of Marques de Cubas (1886)

completed. The stone awarded came from Sigüenza (Guadalajara) and was offered by the quarry-owner Manuel Bueno. Afterwards, a commission presented a report about the field characteristics of the stone and the stone was rejected because there was not good prospects about the supplying. The quarry owner proposed to use another stone coming from Tamajón. In 1906 it was decided to delay the selection of the stone for the main building but it was arranged that Manuel Bueno would supply the stone from Tamajón for the pavement

The Architect Enrique Repullés announced the result of the contest for the pavement of the Crypt during the following year. For that purpose marble from Macael (Almeria) was chosen. The Tamajon Limestones were rejected because the samples did not satisfy the Board (24 Feb. 1907). In the same session the thickness of the pavement stones were set in 5 cm, less than was said in the standards for the contest, and Mr Alguero and son were designated to supply and complete the work.

The previous one is the last reference about the supplying of stones for the Crypt in the first book of minutes of the Building Board meetings.

Economical Features of the Building Work

The economic data referred to in the minutes of the Building Board meetings about financial sources and cost of stones allows us to compare the economy of the Fabric in the Cathedral of the Almudena with older Cathedrals. In the Cathedrals before of the 19th century the Fabric was supported with three types of deposits: Traditional incomes of the Fabric, alms and planned giving and extraordinary deposits (Cortón 1990).

Into the first types were included: The *censos*, which were contracts with properties that produced an annual rent. Only a little part was conceded to the Fabric (Lopez-Arevalo 1966). The *excusados* were tributes exempted to be paid to the King in favour of the chapter. Sometimes the quarriers had the condition of *excusados* (Caso 1981). The Fabric also received one third or one half of the *anatas* that were the annual rents of the belongings of the Church. Other deposits came from the graves or the *impetras* (payment for the right of begging) and a part of the chapter incomes.

In the second types we include all the planed giving offered by unions, monarchs or institutions. These were the main deposits supporting the Fabric. The extraordinary deposits included the collections, donations to Chapter, loans to the Cathedral from little parish churches and sale of chapels, ornaments or jewels (Galera 1982).

In the case of the Cathedral of the Almudena the first type of traditional incomes were non-existent and the main source of incomes was provided by donations from private institutions and non-planned giving. There was also important the extraordinary deposits coming from the sale of chapels, jewels . . .

The first income for the Cathedral was a donation of 880,000 reales coming from some members of the Royal Family. This donation was also the beginning of a public subscription (29th June 1879). The sale of burials and funerary chapels as well as wills that make donations to the Cathedral was the main source of incomes as the crypt was been finished. There were also some cases when was necessary to sale ornaments.

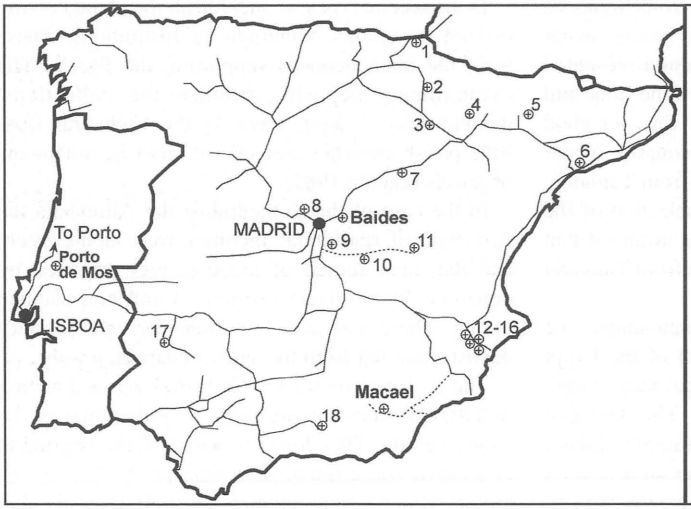
We also find in the minutes economic information about the cost of the stone used in the construction of the Crypt. The three main types of stone used cost the following: Piedra de Baides – 175 pts/m^3; Caliza de Portugal – 240.20 pts/m^3; Mármol de Macael – 41.30 pts/m^2.

Location of the Quarries of the Building

Ways of Transportation.

The supplying of stones is related to the transport ways existing in each age and to the vehicles that dictates the size of the blocks that could be transported. Therefore the ways and means of transport have been a major factor for the selection of building stones and we should consider both factor for the study of historical sources of stone.

The city of Madrid was supplied until the middle of the 19th century mainly with granitic rocks from the Sierra de Guadarrama and with cretacic and tertiary limestones. These limestones was found in outcrops inside the region. The transportation lines at the beginning of the 19th century were to poor, therefore, for large volumes of rock, the distance of the quarries was limited since the transportation of stones was very hard.



1. Rentería Red Marble.
2. Tafalla "Brunette" Limestone.
3. Tudela White Limestone.
4. Luna White Limestone.
5. Fonz White Limestone.
6. Roda de Bará "Brunette" Limestone.
7. Alhama Pinkish Marble.
8. "Berroqueño" Granite
9. Colmenar de Oreja White Limestone
10. Uclés Yellowish Limestone.
11. Arcos White Limestone.
12. Novelda White Limestone.
13. Almorquí Brunette Limestone.
14. Monóvar White Limestone.
15. Petrel Limestone.
16. Sax Limestone.
17. Alconera Bluish Marble.
18. Granada Purplish Marble.

Figure 4
Map showing the railway lines in Spain in 1880 and the localities of the stones proposed for the first contest. Also included in dashed lines are the Aranjuez-Cuenca line ended in 1885 and the Murcia-Lorca line finished in 1894.

The supplying of stone from outside the region began with the setting up of the railway lines. The first railway line was inaugurated 9 de febrero de 1851 and traveled from Madrid to the Royal Place of Aranjuez. That line was lengthened to Alicante in 1858. The company MZA (Madrid-Zaragoza-Alicante) was the owner of that line. As a result of the lengthening of the line new stones were supplied to Madrid because the extraction and cutting of the new stones was cheaper. Figure 4 shows the relations between the railway lines and the stone supplying in the Cathedral of the Almudena. Both the first proposed stones in 1886 and the definitive stones were related with good railway communications.

Petrological Characterization of the Materials

Even when this work is mainly based on the document analisys we should combine both documental and petrologycal analysis to locate the original quarries of a historical building as we said before.

The visual inspection of the crypt allowed us to locate the four stone types mentioned in the minutes. After sampling the building carefully, petrologycal an petrophysical studies have been made. The results of these tests were compared with those made in samples from the possible sources.

The first material is located in the lower parts of the building and came according to the minutes from Baides, Guadalajara. This material is a dolomitic pelsparite. The posible areas were located considering the data obtained from the National Geological Map (MAGNA) and the town council. The area was sampled and after the tests the quarries were located in the Barranco de la Hoz.

Dolostone beds with metric thicknes of the Upper Cretaceous (IGME 1978) were quarried in this area. It can be found cut blocks with toolmarks as remains of the quarring (Figure 5). Instead the stone is mentioned in the minutes as Piedra de Baides, the quarries belongs to the council of Viana de Jadraque at 3 km from Baides and probably the name was changed mainly because the railway station was in Baides.

The second lithology is the main stone type in the Crypt and it is a fossiliferous micrite. The samples from the Building were compared with diferent limestones from Portugal. The results showed that this stone came from the Jurassic Units of the Maciço



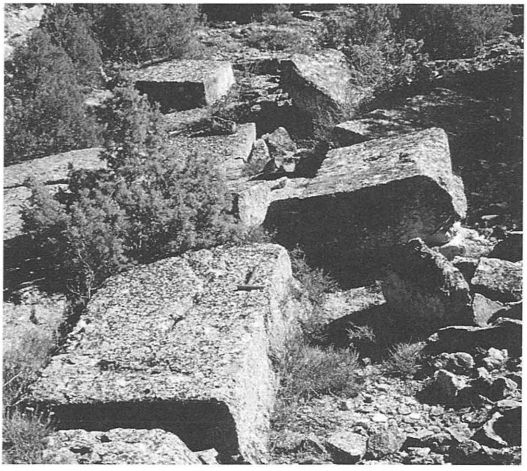


Figure 5
View of the abandoned blocks, remainder of the bedstones quarried in the area of Baides - Viana de Jadraque

Calcário Estremenho and it is related with the stone whose trade name is Alpinina (IGMP 1998).

The chapitels and cut archs of the façade were made of a diferent stone type. Actually, the selected material was not mentioned in the minutes, however it seems probable that this stone type came from Portugal as its supplying overlapped with the supplying of the other. If this premise it is true the stone would be the same of the Monastery of Batalha (Rosal type). The stone in the Building is an oomicrite with fossils but the type of sample did not allow to make tests for the location.

The pavement was made with poligonal granoblastic calcitic marble. The tests showed that this stone used also in other inner elements came from Macael (Almeria).

Conclusions

The construction of the Cathedral of *Santa Maria la Real de la Almudena* lasted for over a century. This length of time is not common in the 19th and 20th centuries even for such a large building. This delay caused the mixture of styles in the building because the original project was changed several times since its beginning. That mixture of neo-styles and its recent character compared to the oldest cathedrals in Spain might be the cause of the lack of studies about this building.

It could be seen that the strong delay in the execution of the building works in the Crypt of the Cathedral was caused not only by the lack of economical resources, but mainly because of the problems with the stone simply due to contracts. This point shows the importance of the stone in a building as a conditional factor in its construction and, of course, its durability.

The vast array of stone studied for the purpose of choosing the best material for the Crypt is detailed. In that way, the first Architect responsible for the building, Marques de Cubas, tried to improve the concept of stone supplying in the Middle Ages. Although that process was carried out with careful attention, we can see how there were many socio-economical aspects affecting the supplying and not related to the rock itself. Even when the Architect criticised that in the older Cathedrals the stone selection was related with the proximity of the quarries it could be seen how strong is the relation between the selection of the stone in a building.

The Crypt of the Cathedral of the Almudena is one of the first buildings in Madrid in which nearly all of the stony materials were from outside the region related to the beginning of new ways of transportation. The study of the ways of transport in

each age and the means of transport have to be taken into account for the purpose of locating the original quarries of stone in buildings.

The petrological and petrophysical tests of the stones of a building are always necessary for the correct determination of quarries of historical buildings as well as the design of restoration works. This work shows that this is not a new concept and that in the second half of the 19th century there was a concern about the previous tests and the durability of the stony materials.

With both document and petrological tests of the building we can conclude that the materials used on the construction of the Crypt of the Cathedral of Santa María la Real de la Almudena were: Dolomitic pelsparite from Baides, Fossiliferous micrite (Pink Alpinina type) from Portugal, Oomicrite with fossils (Rosal type?) and Granoblastic Calcitic Marble from Macael. The masonry was made with the first two stone types. They show in the building a similar aspect because they are both covered by lime. The stone from Baides comprises only the below part of the building. Most of the building is made with the Alpinina type limestone whose quarries are located near Porto de Mos.

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Notes

1. The Marques de Cubas highlighted the importance that had the selection of the stones for an architect: «Una de las cuestiones más difíciles de resolver que pueden presentarse al arquitecto encargado de la construcción de un edificio, es indudablemente la elección de los materiales» (Cubas 1886). He criticised that architects chose the materials hastily, which affected its durability «Hoy, Excmo. Señor, pagamos bien cara la precipitación de aquellos constructores, pues muchos de los soberbios monumentos que la piedad y saber de nuestros antepasados erigieran, amenazan ruina, cuando aun debieran mostrarse erguidos y rasgar las nubes por bastantes siglos más.» (Cubas 1886).
2. Dates in brackets are referred to sessions in: *Libro de Actas de la Junta de Edificación del Templo de Santa María de la Almudena,* 1879–1934.
3. Actually, the monastery of Uclés was not built with stone from quarries of Ucles. Therefore this attribution is wrong. (Lopez de Azcona et al 2001)
4. Both stones from Viana and Baides would be the same materials. The stone from Baides was quarried in an area belonging to the council of Viana de Jadraque.
5. That last stone was referred as the same with which the Monastery of Batalha was built. That could be a clue of the origin of that stone.

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Structural organization and functional distribution of rooms in Madrid architecture of 17th and 18th centuries:

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Several domestic architecture built in Madrid in the 17th to 19th centuries still survey in the historical centre of Madrid, in general with a very poor conservation. In the last decades many of them have been demolished and not always due to a danger of collapse. Nowadays awareness of the cultural heritage is growing in the society and conservation (usually, in Madrid, there are only conserved the façades) is encouraged over substitution. Although this is very positive in general, a rational and deep reflection about the original way of construction and the consequent rehabilitation process itself is missed.

The essential purpose of this paper is to study the origin, evolution and functional distribution of rooms throughout these three centuries and how these changes can be reflected in their structural organization. This study follows three main lines: 1) investigation and selection of the most relevant documents of the 17th to 19th centuries; 2) arrangement and chronological classification, and 3) typological structural classification of them. The main point of the documental approach of this paper is an investigation work based upon the Historical Archives of Madrid and contains: a) graphic information including elevations of the façades, floor plans, sometimes displaying the functional distribution of rooms, and much more rarely, cross sectional views of the building, and b) written information about contracts of works, work conditions, records, architects, clerks of works, etc.

The main structure of this paper follows the next lines: 1) documental historical approach, 2) structural organization of the domestic architecture and, 3) contracts of works: fonctional distribution of rooms.

Documental analysis

The documental historical approach made to reach the aim of this paper follows two main lines: 1) Madrid by-laws, and 2) The original documents found in Madrid historical Archives, that is, a) Archivos de la Villa Secretaría, AVS, and b) Archivo histórico de Protocolos, AHP. The unity system employed in all of these documents are typically castillian feet, castillian finger, etc, and it was not substituted until the end of the 19th century, when the international unity system was generally introduced in works. We will next analyse each type of document.

Madrid by-laws

In this section we have consulted Madrid by-laws beginning a) with those written by Torija in 1661; this by-laws were not real ones as it was not compulsory to follow them, but they served as treatises or guides of construction for builders during two centuries; b) those written by Ardemans in 1719 which were a

recopilation of the previous ones and were also employed as guides of construction for people involved in works, c) the by-laws published during the 19th century (1847, 1854, 1862, 1892); the last ones attended mainly to urban aspects of building design in Madrid, that is, the definition and classification of streets according to building height, which served as a social indicator (the principal or first floor were reserved for upper social class and last floors and attics for workers or lower social class); and finally d) the New Ensanche»s by-laws (1860): at the end of the 19th century a new by-law was published restricted to those new houses that could be built in the new urban areas created in Madrid, the new barrios or also called the «Ensanche». This type of document do not really advance many ideas about the practical distribution of rooms but regulates the maximun heigth allowable in the buildings.

Madrid Archives

The graphic and written original documentation of the functional distribution of rooms in Madrid houses built along these centuries is studied in this section as follows: a) documents found in the Archivos de la Villa Secretaría, AVS, and b) contracts consulted in the Archivo Histórico de Protocolos, AHP.

Archivos de la Villa Secretaría, AVS

This archives are very deep related to the graphic information as they content all the elevations of the façades (it was compulsory to be aproved by the local government before carrying out the works) built in Madrid in these period of time. But in what concerns of the fonctional distribution of rooms, and the information contained in the cross sections, mostly for those houses built in the early years of 17th and 18th centuries, was not often presented. As the 19th century goes forward, the graphic information is more detailed showing in most of the documents analysed not only the façade or several façades when there were, but the individual plans of the different floors, that is, ground floor, first or main floor, second floor and mainly in 19th century third floor; the graphic information of the caves and the attics is only occasionally showed.

In this archives we will show the type of document containing the works licence application; the graphic information including: floor plans, in most of the contracts selected displaying the fonctional distribution of rooms, the elevation of the façades, some cross sections and a graphic scale in castillian feet; and a written information about the people involved in works, such as, architects, clerks of works, owners, builders, construction systems employed, prices of the materials before arriving at works and final construction prices.

Archivo Histórico de Protocolos, AHP: the contracts of work

Once the previous introductional ideas have been set out we can advance that the essential purpose of this paper is to work out an evolution of the essential ideas that lyed in the contracts of works found in the last investigation work done in the Historical Archives of Madrid, AHP, after making a transcription of the original documents. To a better understanding we will follow a chronological study of them. As we mentioned in the previous section, in this contracts we will be also analysing: the type of contract document: 1) new houses construction, 2) rebuilt houses, 3) repairing contracts, 4) houses division documents, 5) title deeds, 6) expert valuation of the houses, 7) renting contracts, etc; the graphic information, that is, floor plans, in most of the contracts selected displaying the fonctional distribution of rooms, elevation of the façades, cross sections, the graphic scale, and the written information, such as, the explanation of the fonctional distribution of rooms.

Main structural organization

From a structural point of view, the main structure of the building was organized, basically, with several bays or spans placed parallel to main façades with a separation of around 15–20 feet and a main court of around 20 feet × 15 feet, placed next to the second span in where the wall sections decreased in respect to the main wall or façade. The construction consisted of a structural wood framework both vertical and horizontal, usually called «entramado» placed over a foundation and a ground floor built both totally with

masonry from the main floor or «cuarto principal» until the roof. The basic criterium to build them lyed in the width of the «carrera», that is, the beam placed horizontally in the walls, and from it they dimensioned the rest of the wood structural elements, decreasing in width as the house grew higher. The spaces left between the vertical and horizontal wood elements were filled with different materials, such as bricks, rough masonry work, sun-dried bridk, etc,. Also the construction of the roofs was solved with a wood structure. This historical construction systems made of wood, in what concerns of the main wooden elements dimensions employed, were pecfectly regulated and controlled by the local government at least from the 17th century, and later on were slowly being substituted by masonry work as most by-laws of that time reflected.

Vertical structure

The maximun hcight allowable for each floor was controlled, as it has been reflected in the table 1, by the local government throughout the different by-laws, so the main vertical wooden elements lenght depended on it, that is, a) the cellar height was usually of around 9 feet height (2.60 meters) and they were totally built with masonry work, b) the ground floor was also built with masonry and had more than 14 feet heigth (around 4,0 meters), c) the main floor was basically built with a wooden framework or totally with masonry of more than 10 feet high (around 3,0 meters); d) the second floor, third floor, fourth floor, etc, of around 10 feet (aproximately 3,0 meters), and e) the attics height started to be controlled in the 19 th century and they should be of more than 9 feet height (2.60m). An example of it can be seen in figure 1.

WOOD STRUCTURAL ELEMENTS MAINLY USED					
	NAME	DIMENSIONS			
		Length feet	Width feet/fg	Height feet/fg	
VIGAS	VIGA DE MEDIA VARA	< 30 > 30	1 ½ f	1 f	
VIGAS	VIGA DE PIE Y CUARTO	< 30 > 30	1 1/4 f	1 f	
VIGAS	VIGA DE UN PIE TERCIA Y CUARTA	< 30 >38	1 f	3/4 f	
VIGAS	VIGA DE CUARTA Y SEXMA	22-30 > 30	3/4 f	½ f	
VIGUETA	VIGUETA DE A 22	22	3/4 f	½ f	
VIGUETA	MEDIA VIGUETA DE A 12	12			
MADEROS	MADERO DE A 6	18	11 1/2 fg	8 fg	
MADEROS	MADERO DE A 8	16	9 fg	7 fg	
MADEROS	MADERO DE A 10 DOBLE	14	7 fg	5 fg	

Table 1



Figure 1
Vertical structure. C/ Ventura de la Vega

The vertical structure was organized as follows: a) main walls, b) secondary walls or thin walls, c) partywalls,and d) partitions.

a) The main walls were built in the main bays or spans, that is, they were located in the main façades, in the internal walls following the direction of façades and in the interior court walls. These main structural walls usually decreased in section as the façade wall grew higher being the wall inicial width around 3.0 feet and this section was reduced a quarter of a foot each upper floor until the last one which had 22 feet width.

b) The thin walls, «cítaras» or «tabicones» (or thick partitions) were secondary or «traviesa» walls

that cut main walls perpendicularly. They had a width of 3/4–1 foot (21–28cm) and were located in interior court walls, interior walls and staircases. The section of the wood elements used in the «cítaras» also decreased as the house grew higher. That is, the ground floor used beams of tercia, the main floor used beams of sesma, the second floor beams of «maderos de a 6», the third floor beams of «maderos de a 8», and so on.

c) The main structural fonction of the party-walls was the lateral or back separation of neighbouring houses. They had a width of 3/4–1 foot (21–28 cm). Clerks of works used to build them perpendicular to main walls and to the rear of houses. As with the main walls discussed previously, the vertical section of masonry party walls also decreased with height, being reduced by around 1/4 feet in width at each floor. In this way party-walls had a typical width of 3.25 feet at the ground floor, 3.0 feet at the main floor, and so on until the roof.

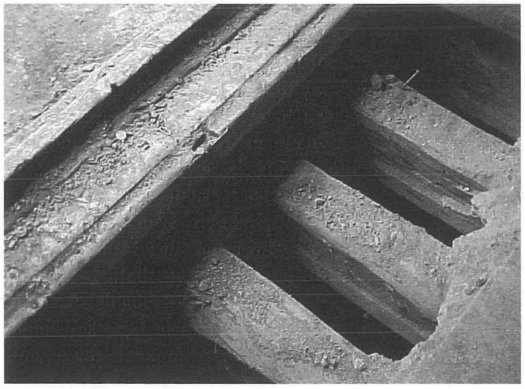


Figure 2
Wood horizontal structure. C/ Relatores

Horizontal structure

Historically floors were built in wood until the end of 19th century, when they began being built with steel beams. The horizontal structure, as it can be seen in figure 2, consisted of a frame of timber beams supported in main walls covering main spans of floors; in buildings of only one bay (span), for very small distances (3.0–4.0) meters, the beams were directly supported on the masonry or timber-framed walls; when the spans were of medium length, that is, (5.0–7.0) meters, the beams were placed perpendicular to main walls and small beams following the direction of main walls; in those houses with large spans, that is, (8.0–9.0) meters, it was recommended to build the house with two bays (spans) following the timber beams the longitudinal direction. The perimetral supports were solved whether in the lateral party-walls or in the façade and back court walls. The central supports were solved with pillars or with secondary walls or «cítaras». Even if the spans were in every floor the same, the section of the timber framed floors could vary depending on the height of the house: main floor, second floor, third floor, etc.

Functional distribution of rooms

The inclusion in the houses fonctional distribution of rooms of several spaces destinated to a concrete domestic fonction, such as, courts with a well, kitchens, dormers or attic windows («boardillas»), windows at street level in cellars («lumbreras» or «troneras»), etc, as most contracts and records of works in the historical archives mentioned, always were a concern in the construction process but, as it was not compulsory to sign a contract of work before building a new house, there are not many documents in which this evolution can be studied. Nevertheless in those analysed showed an original information mainly for two reasons: the scant investigation work done until today in this subject, and the relevant details that can be studied if compared them altogether. The main fonctional distribution of rooms attending to the people that owned the houses can be classify in two groups: a) Individual houses, and b) Tenment houses or renting houses and among them, the typical and so called «corralas».

Individual houses: general functional distribution of rooms

This houses had an owner who lived in the so called first floor or main «room» and other floors or rooms used for «servants» or for renting them. Usually when relating to Madrid houses is very often seen to called each floor as «cuartos». Historical houses built in Madrid, principally

those placed in main streets, often had stores in the ground floor and cellars or undergrounds under them. Both were communicated by staircases or even provisional stairs. Typically the houses had four or five floors over the cellars: ground floor, main floor, second, third and attics (roofs), depending on the width of the street they faced. We will study all these aspects starting from the underground level.

Underground floor or cellar (also called «cueva»)

As we can see in the façades plans they used to build an underground floor or a cellar of around 9 feet under the street level. It was communicated with the ground floor by an staircase and sometimes even with a provisional ladder. Usually they opened small windows called «lumbreras» facing the main façades to ventilate and to light them.

Ground floor

If the house had a cellar, the ground floor was usually elevated some feet above the street level. We can find a wide information about the fonctional distribution of rooms at this point because it was nearly the only floor drawn. The houses usually had two entrances in the main façade: 1) a big door destinated to the livery stable and linked with the stable and an interior court with a well, and 2) a house main entrance with an entrance-hall («zaguán») and linked with the main staircase. This functional distribution of rooms can be seen in the following document containing an elevation of the façade and two floor plans: the ground floor with the following distribution: 1. entrance-hall, 2. way to the stable, 3. main staircase, 4. main «sala», 5. second «sala», 6. secondary «sala», 7. «alcoba», 8. stable, 9. livery stable, 10. courtyard, and in the first or main floor with the numbers: 1.

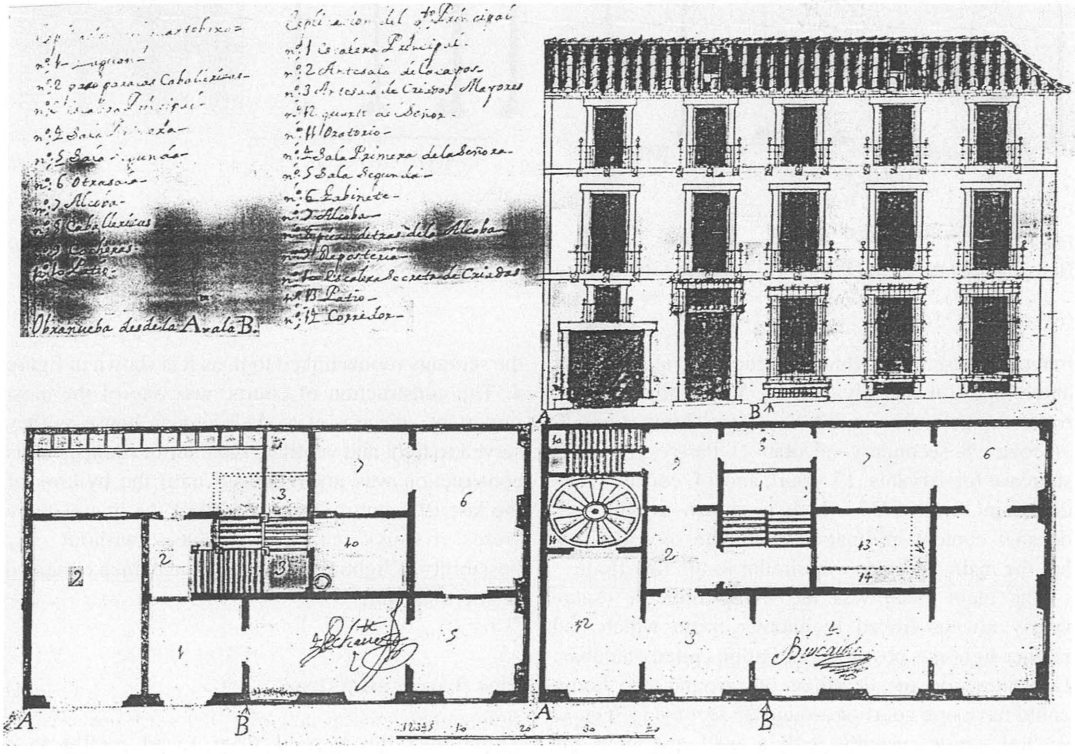


Figure 3

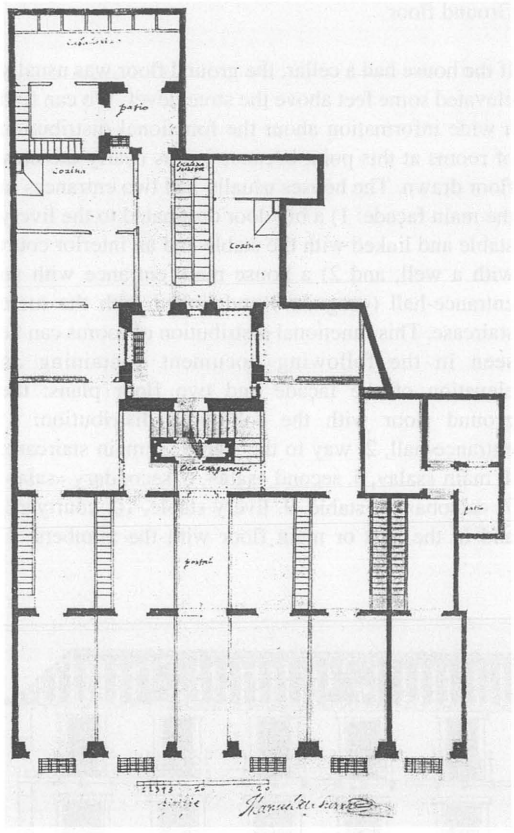


Figure 4
House built in the Puerta del Sol (1729). 1.66.136

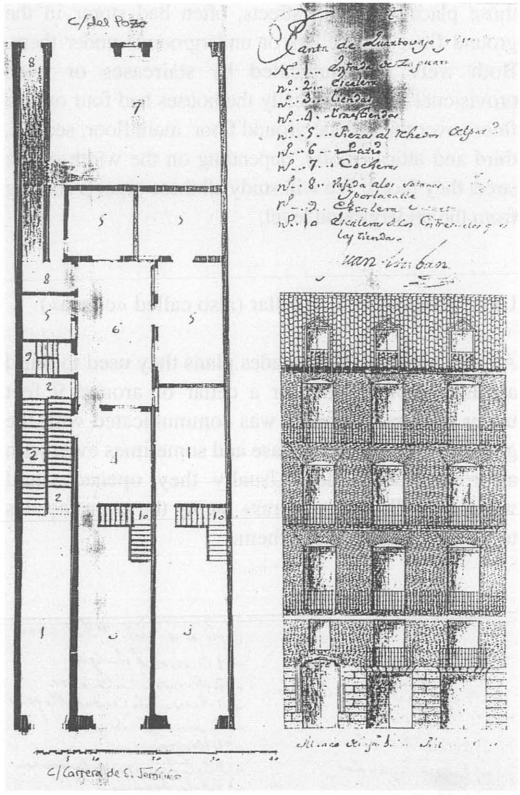


Figure 5
House built in C/ Carrera de S. Jerónimo y c/ del Pozo (1750). AVS. 1.84.128

main staircase, 2. servants anteroom, 3. old servants anteroom, 4. main lady»s room, 5. secondary lady»s room, 6. «gabinete» or lady»s private sitting room, 7. «alcoba», 8. secondary «alcoba», 9. Pastry, 10. secret staircase for servants, 13. court, and 14. corridor. The document from 1737 which is shown in figure 3, doesn»t content infomation about the second floor, but the main structure was similar to the first floor.

The main room was the living-room or «sala» nearly always linked to another room which had neither light nor possible ventilation called «alcoba». Depending on the depth of the ground, the house could have one court of around 20 feet by 15 feet, or several courts, usually with a well and with the kitchen near them. When there were a secondary court, it had often a secondary staircase, a kitchen and the servants rooms linked to it, as it is shown in figure 4. The construction of courts, was one of the most important «pieces» of a Madrilennian house as they served to light and ventilate the interior rooms, but its construction was not regulated until the by-laws of the last 19th century.In nearly all of the houses there were «rooms» called «alcobas» without any possibility of lighting nor ventilation, which remained linked to a main room.

First floor or main floor

Sometimes the ground floor faced totally to a commerce street and all the rooms at street level were not living rooms but secondary ones wether

«cocheras», kitchen, houses stores, or destinated to shop stores, leaving in that case the upper floor, that is, the first floor, as the main one. This can be seen in the figure 5 shown below. In this case the house faced two streets, to the main one, c/ Carrera de S. Jerónimo, three rooms, the main entrance linked to the main staircase and two stores each one with an individual staircase linked to an upper floor or entresol and with a backstore facing the courtyard; and a secondary one, c/ del Pozo with the livery stable and a secondary entrance linked to secondary rooms: the cellar, a secondary staircase and some rooms around the court. The functional distribution of rooms is the following: 1. entrance hall, 2 staircase, 3. store, 4. backstore, 5. rooms around the court, 6. court, 7 livery stable, 8. way down to the cellar, 9. secret stairs, 10. stairs to the entresol. As in the previous figure there is no information about the rest of the floors: first floor or main floor, second, third and attic. In the upper floors the access to the interior rooms was solved by the corridor, a narrow way built over the courts.

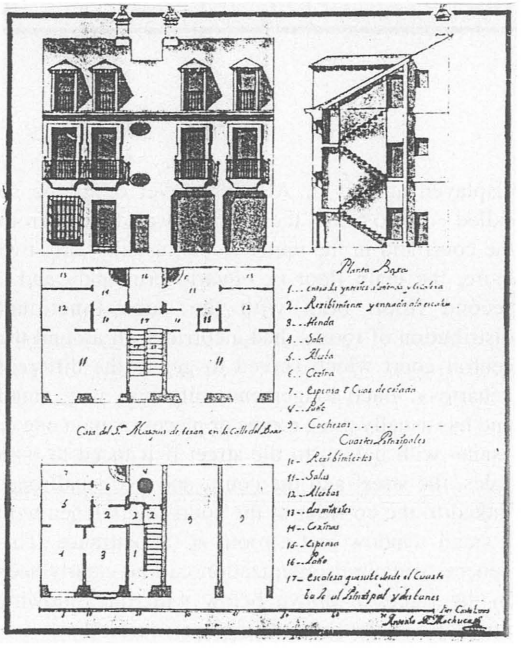


Figure 6
Marqués de Terán»s house in the C/ del Barco (1760). AVS 1.45.87

Second floor, third floor, etc:

This floor had a very similar organization as the first or main floor and repeated the basical organization of the functional distribution of rooms. The main rooms faced the streets and the secondary rooms, kitchens, servants rooms, etc, were left to the back part or to interior courts.

Last floor or attics

In the last floor of the houses there were the so called «desván or buhardillas» which were not living rooms (the heigth was of very few feet) but, in practice, they were in the early years the servants rooms and later on, in the 19th century, when owners started renting the houses to workers, the home for several families which couldn»t afford a better lodgement. One of this kind of houses shown in the figure 6, is organized following the main ideas explain in the previous lines. The information about the fonctional distribution of rooms is the following: 1. entrance to the store, the «alcoba» and livery room, 2. receiving room and entrance to the staircase, 3. store, 4. living-room, 5. «alcoba», 6. kitchen, 7. servants room and storeroom, 8. court, 9. livery stable, and in the main floor with the numbers 10. receiving room, 11 rooms, 12. alcobas, 13. bedrooms, 14. kitchen, 15. store, 16. court, and 17. main staircase.

In 17th and 18th centuries the houses often had a yard or «corral» in the back part of the house with a simple adobe wall which separate those from the neighbouring but, as the town was growing, new houses were built in the backpart often with no lightint to streets but to interior courts.

The possibility of building attic windows or dormers existed during 17th–19th centuries and was a controversial subject in the by-laws of domestic architecture in Madrid. Due to health and hygien considerations, it was frecuently debated whether to allow or to forbid them. From a construction point of view, Ardemans (1716) and some other clerks of works always pointed out that they should be built in the same vertical line as main walls and ligned with windows and balcons and never facing party-walls. At the end of 18th century, Villanueva (1790) suggested to suppress them, «as the experience always reveals that through them the fire spreads

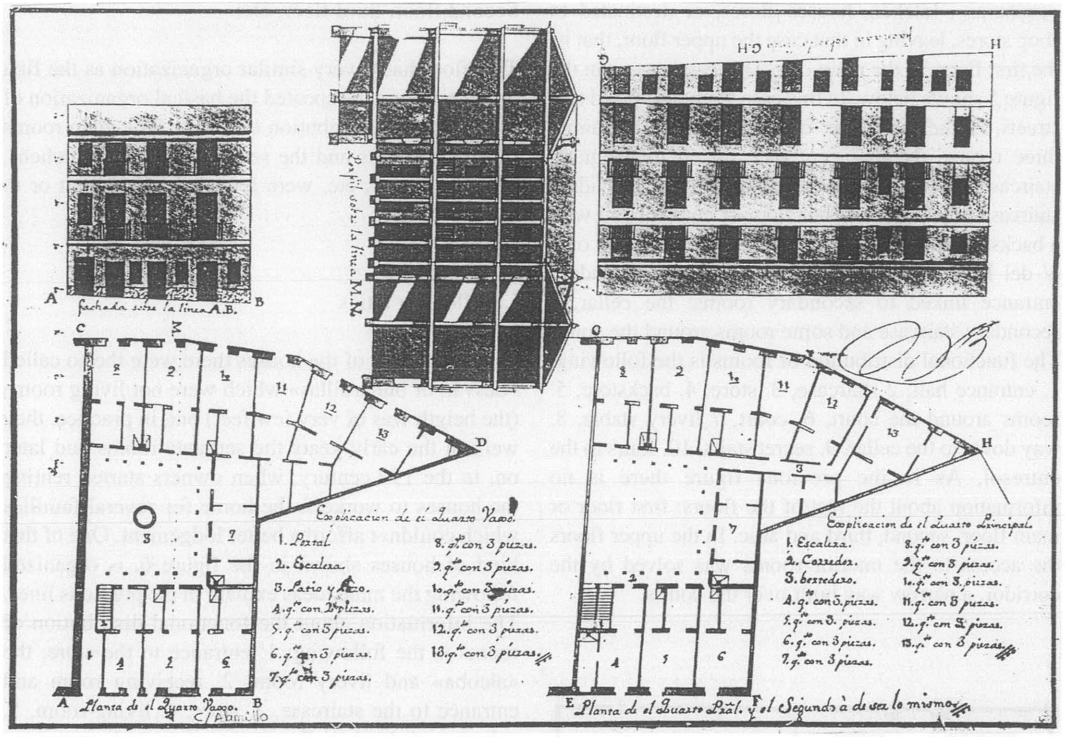


Figure 7
A «corralas» house built in Madrid in 1757. (AVS 1.45.140)

promptly». Nonetheless they would not be forbiden until the «Reales Órdenes» of 1854. In the «by-laws of 1892 this prohibition is kept and also the fact of allowing to use attics as living rooms, except those placed at the backs and which were over 9,0 feet in height.

Community houses or renting houses

The «corralas houses» is a typical community madrilennian house built along these three centuries and some still survey in the historic centre of Madrid. The «corralas» walls were made of open wooden framing of vertical and horizontal timber elements which supported the galleries around the interior courtyard. Its basic structural organization is a quite big central court with a staircase and several small «lodgement unities» or «cuartos» displayed around it. At street level or in the so called «cuarto baxo» the entrance was directly from the court and in the upper floors, usually only two more, the main floor or «quarto principal» and a second floor, both with the same functional distribution of rooms, had a corridor all around the central court which served to get to the different «cuartos». Each lodgement unity was very small and has usually three rooms or pieces: a main one or «sala» with balcon to the street if it faced to both sides, the street and the court, and two small ones linked to the corridor at the court: the kitchen with a small window and a room at the entrance. This general structural organization can be clearly seen in the figure 7 shown below with the following numbers, in the ground floor or «cuarto baxo»: 1. entrance, 2. staircase, 3. courtyard and well, 4. lodgement with two rooms and from number 5 to number 13 all the lodgements with three rooms and,

in the main floor, and as it is said in the plan with the same structure for the second floor, the following fonctional distribution of the lodgements: 1. staircase, 2) corridor, 3) dumping place, and from number 4 to number 13 all the lodgement unities with 3 rooms,

In what concerns the regulation of including a special room in each house for a toilet did not exist until the end of 19th century. First the toilets were the farmyard of the houses, later on works included a comunnitary toilet, called the «comun», located at the end of a community corridor, and in the last years of the 19th century the new by-laws in the new urban areas of Madrid included several regulations about it, but even in the 20th century many unity lodgement had not an individual toilet.

THE CONTRACTS OF WORK

In the previours section we have shown a general revision of the main fonctional distribution of rooms. In the following lines we analyse the main contents of the contracts of works related to this purpose following a chronological exposition of the contracts of work. This study also includes the most relevants plans of each period of time and some parts of them which have been literally transcripted.

The contracts of work in 17th century

The first document analysed in this paper is a contract of work of a house built in Madrid in 1626 which

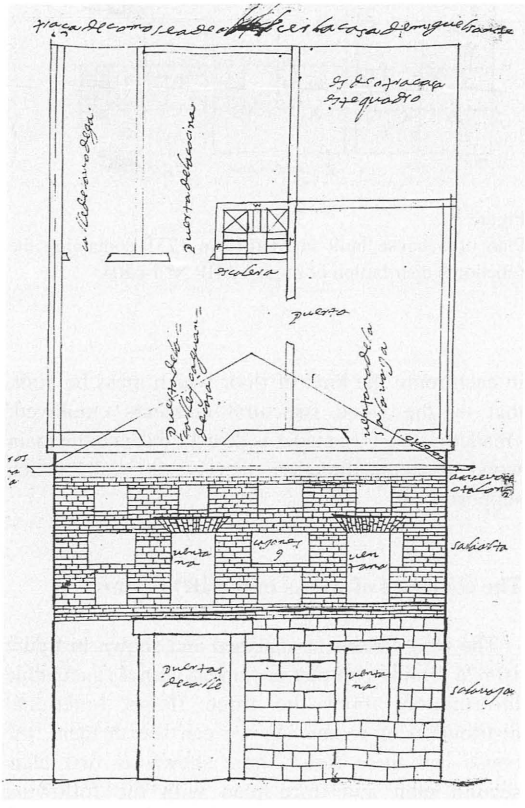


Figure 8
House built in Madrid in 1626. Ground floor and elevation of the façade. AHP. Nº 38.028

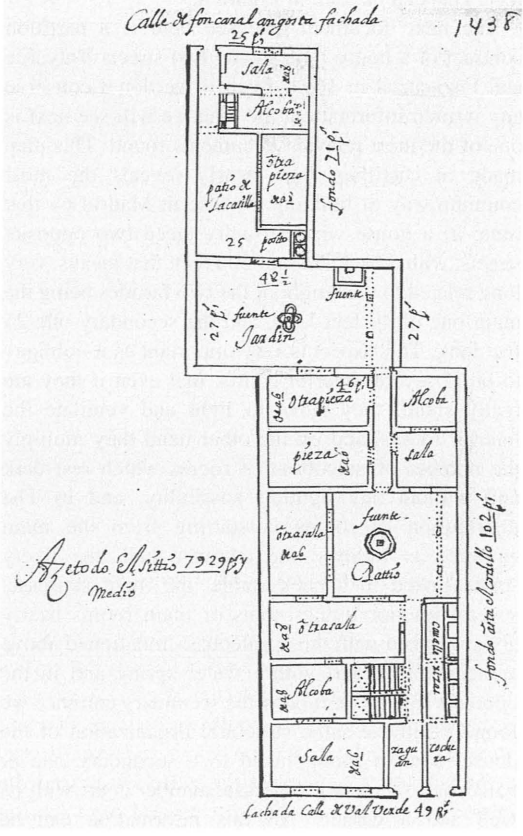


Figure 9
House built in Madrid in 1694. AHP Nº 12.259

shows the elevation of the façade and the first floor with some notations on it. We can observe an original superposition of both of them. The displaying of rooms is as follows: a ground floor, also called «sala baja»which includes: the main entrance with the entrance hall linked to the staircase, the secondary entrance and the kitchen, and a living room; a first floor, also called in the elevation of the façade, «sala alta», containing the main rooms and the last floor built in a lower height used for servants. This document doesn't content any scale or measurement unity system, but as it can be clearly seen in the graphic information, the walls were built with different widths: the main structural wall, the façade, is about three feet width, the interior structural wall is about two feet width, and the partywalls which are represented beside the neighbouring ones are of around half the width of the façade, that is around $^1/_2$ feet. This can be seen in Figure 8.

The next document analysed here is a partition contract of a house built facing two streets Valverde and Fuencarral in 1694. Even if we don»t conserve any written information, the plan we will see next is one of the most relevant documents found. This plan made in castillian feet clearly reveals the most commun way of building a house in Madrid by that time: a) a house which usually faced two opposite streets, with a back lenth of 200 feet, that means, very long related to the lenght of the two façades being the main one of 49 feet long, and the secondary one 25 feet long. This aspect is very important as it «oblige» to build several interior courts, that even if they are really small, they serve to light and ventilate the interior rooms, and on the other hand they multiply the number of «alcobas» or rooms which rest dark and without any lighting possibility, and b) The distribution of rooms is starting from the main entrance as follows: the entrance hall, the livery stable linked to a back stable, the main staircase, several interior living-rooms or main rooms nearly always linked with those «alcobas» mentioned above and a central court with a water spring and in the opposite side or starting by the secondary entrance we found again the same structural organization of the house: a main room linked to a secondary one or «alcoba, a secondary staircase, another court with its well and a garden. All this information can be consulted in the graphic shown in figure 9. One of the most relevant information given in it is that includes

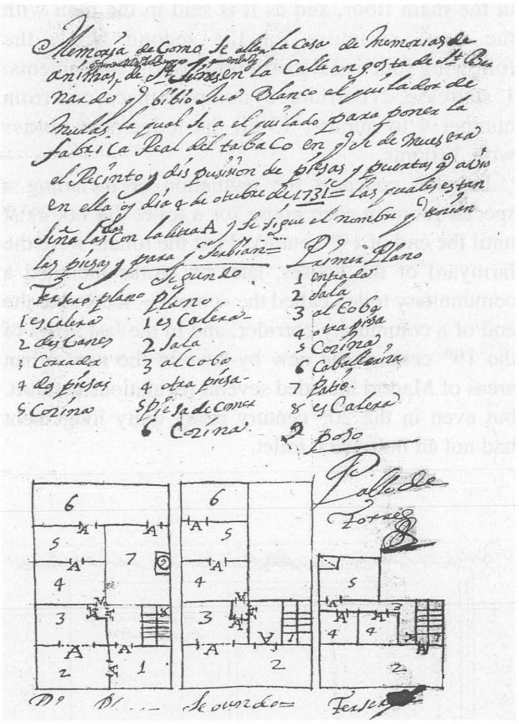


Figure 10
Plan of a house built in Madrid in 1731 containing the functional distribution of rooms. AHP N° 14.404

in each room the kind of floor which muss be built, that is, the wood structural elements employed: «maderos de a 6'», maderos de a 8', etc, and the main wood elements direction, that is, the walls which support them.

The contracts of works in the 18th century

The next document analysed and shown in figure 10 is a renting contract document with a squemathic information about the three floors functional distribution of rooms. As we can see in them, the house had three floors, here shown as first plan, second plan and third plan with the following distribution; for the first one: 1. entrance, 2. «sala» or main room, 3. «alcoba», 4. room, 5. kitchen, 6. stable, 7. courtyard, 8. staircase and 9. well. In the second

floor: 1. staircase, 2. «sala» or main room, 3. «alcoba», 4. room, 5. dinning-room, and 6. kitchen; and in the third plan: 1. staircase, 2. Dormers, 3. Corridor, 4. two rooms and 5. kitchen.

The next document selected in this section is a very detailed new house building contract containing graphic and written information about the the fonctional distribution of rooms. Related to the first one and as we show in the original document in figure 11, the distribution of rooms is as follows: 1. main façade, 2. entrance hall, 3. main staircase, 4. livery stable, 5. «Cuarto bajo facing the street, 6. Interior rooms, 7. corridor, 8. rooms imposible to get to them in the upper floors, 9. main courtyard, 10. small courtyard, 11. rooms facing the small courtyard

. . . Plan de la casa del señor D. Francisco Gedeon y Hinojosa, de la Calle de la Magdalena, se entenderá del modo siguiente. Fachada principal a dicha calle de la Magdalena se demuestra con el numero 1. Zaguan nº 2. Escalera principal nº 3. Cochera nº 4. Cuarto bajo a la calle nº 5. Piezas interiores nº 6. Corredor nº 7. Piezas que no se llega a ellas nº 8. Patio principal nº 9. Patio chico nº 10. Piezas al patio chico nº 11. Caballeriza nº 12. Piezas que dividen los dos patios 13 . . . AHP Nº 16.430 (1737).

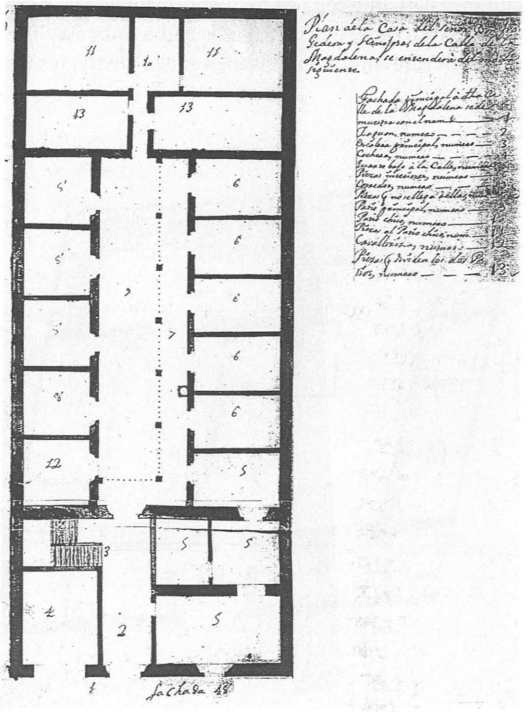


Figure 11
Rebuilt house contract. AHP Nº 16.430 (1737)

Related to the written information, it makes a general description of the main structural way of building it literally says:

. . . Primeramente a dicha Calle de la Magdalena se ha de labrar en sus quarenta y ocho pies de líneas que tiene de fachada, en lo bajo a la izquierda de su entrada un cochera, y sobre ella y el resto de habitaciones bajas en sus dos crugias, un quarto principal, precediendo para ello primero el repaso que necesitaren las paredes Maestras, que oy ay, como tambien en la linea de mano derecha de su entrada, se ha de labrar dos crugias de piezas, una de quartos bajos; otras sobre ellos al piso del quarto principal, que va mencionado, con su corredor de cinco pies de ancho, precediendo primero para él de las basas de barro que sean convenientes y sobre ella sus pies derechos con sus zapatas y en el segundo cuerpo sus pies derechos, y de uno a otro sus antepechos de tabique y cubiertos con cielo raso de quadrado: de modo, que todo lo que ay que labrar desde los cimientos a los tejados, demuestra en el Plan el numero 6. Y el numero 7. El numero 5. El numero 2. El numero 3. Y numero 4. Y numero 12. Y se previene que los demas numeros del Plan son piezas antiguas, las que han de quedarse como oy están,que todo lo expresado, executado con madera de Corral y buena mezcla de cal y arena, con los demás materiales que para ello se necesitan, puertas y ventanas con sus errages, . . . AHP Nº 16.430 (1737).

The next document is an expert valuation of three houses. For the three of them, the main structure of the document is very similar: a) an emplacement description, b) the house and the construction systems employed description, and c) the final valuation of both, the emplacement and the house. The most relevant information shown for this paper is related to second part, the distribution of rooms and we will refere only to it. For the first valuation, the house rooms are the following ones (the plan shown in figure 12 is related to the main floor) beginning from the C/ Flor Alta: living-room, «alcoba», kitchen, servants room, dining-room linked to the courtyard, courtyard with its corridor, receiving room and main staircase, and in the opposite street, beginning from the staircase: receiving room, courtyard linked to an

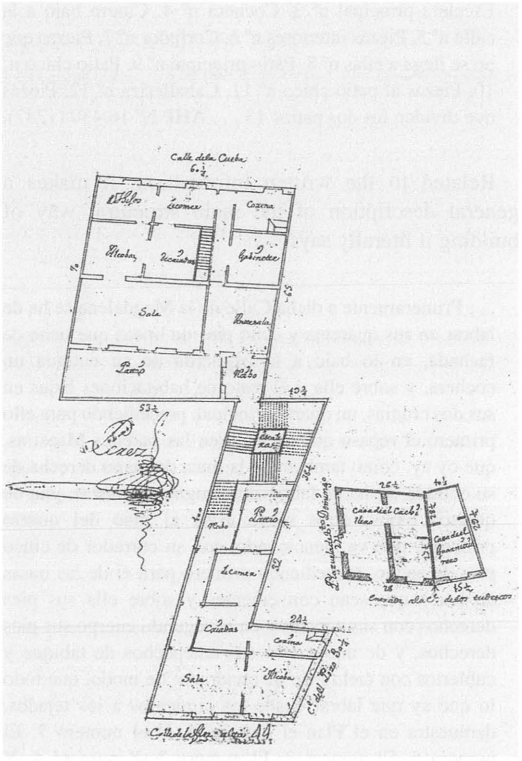


Figure 12
Plan of the houses. AHP Nº 16.366 (1741)

anteroom and the living-room this one beside the «alcoba» and the servants room with a secondary staircase, a no lighted private room and facing the backstreet c/ de la Cueva: the dining-room, the kitchen and the childrens room. They are mentioned in the next lines the main distribution of rooms

> . . . Como se demuesttra en el mapa que queda figurado, hacen de area superficial: siette mil cientto y veintte y ôcho pies y medio quadrados de sittio, con lo que le ttocâ y pêrttenece de sus medianerias, â los qualess dandoles su justto valor, como â la fabrica de que se componen sus viviendas; y es en la fachada principal en lo bajo su zaguan, pattio, cochera, y cavalleriza en los sottanos, y la escalera principal; un quartto principal de siette piezas y enzima quartto segundo y tercero, cada uno de seis piezas y un paso y desde dicha escalera principal se manda para un quartto bajo y un principal, cada uno de nueve piezas, que cae â la fachada de la calle de la Cueva . . .Nº 16.366 (1741).

For the second house there is not any relevant information related to its rooms, and about the third one it says:

> . . . Y haviendole dado a este su justto valor, como â la vivienda de una tienda Cuchilleria, con su pieza dettras y devajo un poco de cueva, y pedazo de sottano, y enzima de la tienda su desban gattero. A la fabrica que es una tienda trasttienda, escalera para subir âl quartto principal que se compone de sala y alcobamiento esttrecho y ttodo mui malttrattado, valen segun âl presente se hallan, sittio y fabrica, diez mill cientto y seis Reales Vellon . . . Nº 16.366 (1741).

The next document studied in this section, is as the one mentioned just above, another expert valuation of a house, this document shown in figure 13 follows the same structure as the previous one being in this case a house with a «wine cellar». In what concerns the functional distribution of rooms it contains: main entrance hall, thirteen rooms, a wine cellar and a wine press, two rooms, two courtyards and a staircase. The most relevant information is mentioned nextly, it says

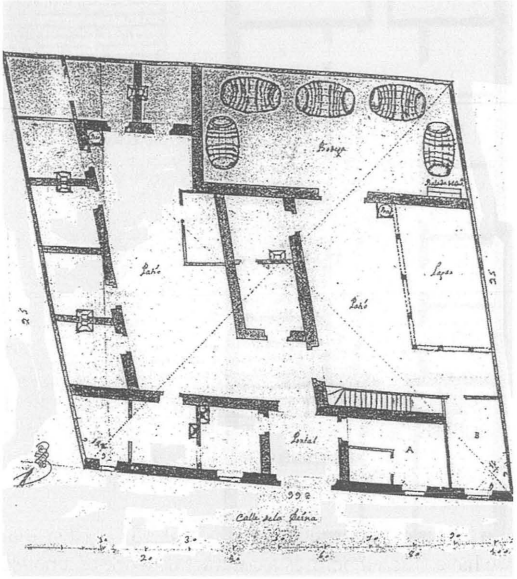


Figure 13
Wine cellar house. AHP Nº 16.300 (1742)

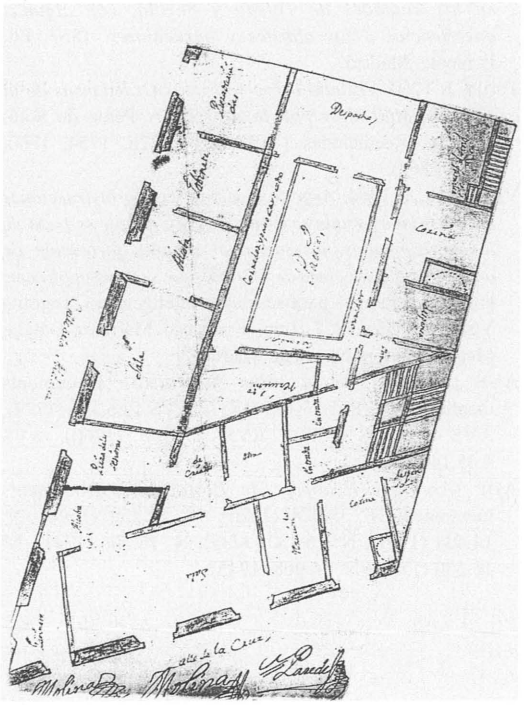


Figure 14
House built in Madrid in 1745. AHP Nº 16.968

. . . Asimismo ha medido la avittazion de que se compone dicha cassa que es porttal, ttrece piezas, lagar y bodega ttodo a teja barra y dos piezas de suelos de bobedillas que son las que señalan el dicho y dos pattios ttodo ello segun conforme se demuestra en la plantta adjuntta.Y su fabrica se compone de zimienttos de piedra de pedernal, tapias a piedra y pilares de albañileria, zerramienttos de taviques, suelos de bobedillas de madera de â ocho, armaduras de la misma madera y de a seis, chimeneas, puertas y venttanas con sus errages, dos rexas en la fachada de la calle, lagar, solado de losas verroqueñas. Dos pozos empedrados, la maior parte de la cueba vesttida de fabrica de albañileria, zinco cubas pilon, viga, y 8 sillo, veinte y ocho tinajas de diferenttes tamaños contando lo demas de que se compone dicho sittio y pelttrechos de Bodega . . . AHP Nº 16.300 (1742).

The next and last document of this 18th century that we have studied here, is a contract of work of a house built in a corner of the C/ de la Cruz and c/ de la Aldava in 1745, which is as follows.

. . . Y el quarto segundo que oi son desvanes se ha de formar dos quartos vivideros de sala, alcoba, cozina, y dos piezas, el uno â la calle de la Aldaba, y el otro á la de la Cruz, y lo restante del zentro de dicha casa se han de dejar viviendas para los criados que han de servir en las viviendas de los quartos principales. Y se de hazer pajar y blanquear â lecho todas las viviendas y hazer quatro chimeneas para las quatro viviendas nuevas y en los quartos de los criados las que fuesen precisas dejandolo rematado todo de yeso negro y blanco y la escalera principal, y hazer corredores de tabicado en dichos quartos para su comoda habitazion poniendo las puertas nuevas que faltasen con todos sus herrajes y en las viejas los que faltasen como en las ventanas que oi tiene aprovechando toda la madera teja y tabla que fuese de provecho como puertas, ventanas y balcones y los que no se an de hechar nuevos como recorrer todos los solados de todas las habitaciones de dicha casa, y se â de revocar las dos fachadas y quartos nuevos que se hagan, y rematado . . . AHP Nº 16.968 (1745).

Conclusions

Houses built in Madrid had in general a very large depth ground related to the extend of the main and secondary façades which obligated to built a succesion of several courts to light and ventilate the interior rooms, but they still left many rooms without any possibily of lighting nor ventilation, the so called «alcobas». The regulation of including a toilet didn»t appear until the last years of 19th century building them, in general, in the corridors. Houses had several staircases, the main one was near the door entrance and a secondary one was in general built in the last part of the house and near the kitchen and the servants room. Related to the main dimensions of the structural elements, the historical approach made throughout the documents analysed verified the uniformity of the structural wood elements, both vertical and horizontal, used to build the frames along this time, so the small variation of the functional distribution of rooms did not have an effect on the structural organization of the houses construction.

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Wooden framed structures in Madrid domestic architecture of 17th to 19th centuries

E. González. Redondo
R. Aroca Hernández-Ros

Structural decay in masonry buildings from the 17th to 19th centuries is very common in Madrid mainly because of poor conservation in which normally a complex pathology where cracks of different kinds appear. At present, very few studies have investigated the historical construction aspects to acquire an understanding of the morphology and the structural behaviour in order to determine the real repair needs in an intervention. This paper follows some previous ones (González and Aroca 2000; González and Aroca 2001a; González and Aroca 2001b) where there have been introduced the masonry structures and the wooden framed construction systems used in Madrid from the 17th to 19th centuries. In this one we pretend to go further in the understanding of the historical constructions which still survey in Madrid.

The starting point of this paper is related to a documental historical approach based upon the Historical Archives of Madrid. This study follows four main lines: a) investigation and selection of the most relevant contracts and documents of the 17th to 19th centuries for an individual and an altogether analysis of the evolution of the construction systems used in Madrid in that time; b) transcription of such documents; c) an individual study of the structure, methods and contents of each document, such as: people involved in works: architects, clerks of works, builders, owners, etc; and d) an altogether analysis of them with the aim of setting the origin, evolution and transformation of the construction systems used in Madrid. To a better understanding, this study will be completed with the addition of original plans, graphic construction details and the original transcription of some abstracts of the documents consulted.

Documental historical approach

As it has been introduced in the previous lines, the main point of this study is related to a documental historical approach based upon the Historical Archives of Madrid. The kinds of document consulted and transcripted is very wide, most of them belongs to two main groups: a) the documents looked up in the Archivo Histórico de Protocolos, AHP, and b) the archives consulted in the Archivo histórico de la Villa, AVS.

Contracts of works contents (AHP, Archivo Histórico De Protocolos)

The first group of documents belongs to the contracts of works, and among them are included: 1) new houses construction contracts, 2) rebuilt houses contracts, 3) repairing contracts, 4) houses division documents, 5) titles deeds, 6) expert valuation of houses, and 7) renting contracts. Those from which we can take out a more detailed information are the real contracts of works. As architects, clerks of

works, builders, owners and other people involved in works were not compelled to sign a contract of work including: work conditions, material prices, paying conditions, etc, there are only conserved some of them. Works in Madrid were usually carryed out following a house building tradition.

The contents of the documentes consulted in the Archivo Histórico de Protocolos, AHP, include the original documentation of contemporary domestic architecture built in Madrid, that is: a) written information, and b) graphic information. A general approach to the first one can be seen in the next lines that belong to an expert valuation of a house where there are analysed, in the first lines, the fonctional distribution of rooms containing a cellar, courtyard attics, different rooms, main floor, etc, and in the next ones, the different construction systems employed in the foundations, façades, internal walls, partywalls, floors, roof, and finally the price of the expert valuation

> . . . Un sottano, pattio y desbanes, y enzima de dicho quartto principal y caja de escalera, tres quarttos ô viviendas de dos piezas cada uno. Todo lo que estta fabricado de zimientos de mampostteria, vaciados de tierra, cantteria en la fachada principal. Una porttada moldada, de jambas, denttel y battientte, con su cornisa enzima, y la de el pozo sus dos hiladas de canteria y lo resttante de fabrica de albañileria, y la fachada de la calle de la Cueva, de mâchos y cajones de tierra y en lo intterior fabrica de albañileria y machos de lo mismo, tapias de tierra, zittaras, tabiquess, suelos de bôbedillas, de ttodos tamaños, con solados de ladrillo y de yesso. Armaduras, aleros y guardillas con su tabla y teja, canelones de plomo, y de ôja de latta, puerttas y venttanas con sus herragess y rejas, balcones, ânttepechos y barandas de fierro. Solados de barroqueña y canales de lo mismo, pozo con brocal de cantteria, cuevas, sottanos, empedrados, medianerias, pesebres y lo demas de que se compone lo referido, lo tassó, ttodo que vale. Segun âl presentte se halla, sittio y fabrica, cientto y ôchentta y nueve mill trecienttos, sesentta y zinco Reales de Vellon . . . AHP. N1 16.366 (1741). Expert valuation of a house.

and, in the graphic information we will see the elevations of the façades and floor plans, sometimes displaying the functional distribution of rooms, and often including a graphic scale, nearly always refered to castillian feet. In the figure 1 we show a contemporary document.

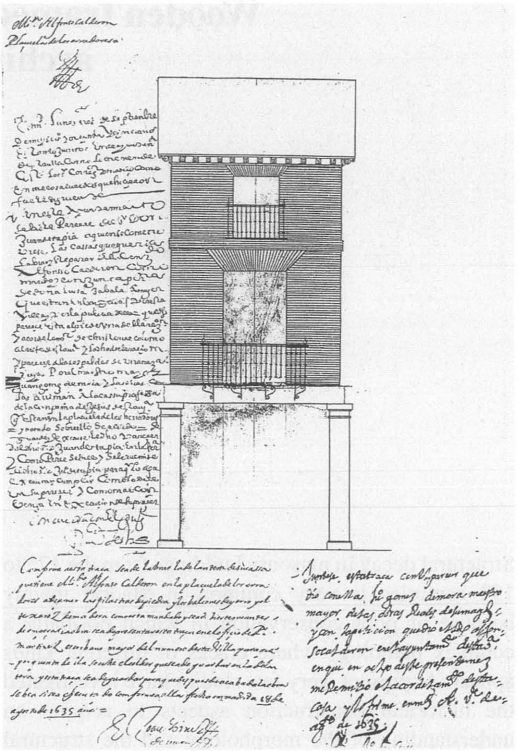


Figure 1
House built in Madrid in 1635. Contract of work. AHP N° 2.692

«Works licences application» (AVS, Archivo de la Villa Secretaria)

In the second group of the documents consulted we find the «works licence applications» which were compulsory to be approved by the local government before starting and carrying out the houses construction. These documents should include the elevation of the façades and a general written information about the work conditions. Optionnally added a wide graphic information, such as, the different floor plans with the explanation of the fonctional distribution of rooms and very rarely cross sections. In this second group of documents the most significant information is connected to the graphic information because, in practice, the reduced lines of the work conditions were a mere procedure to obtein the «contruction licence». In the figure 2 is shown this kind of document.

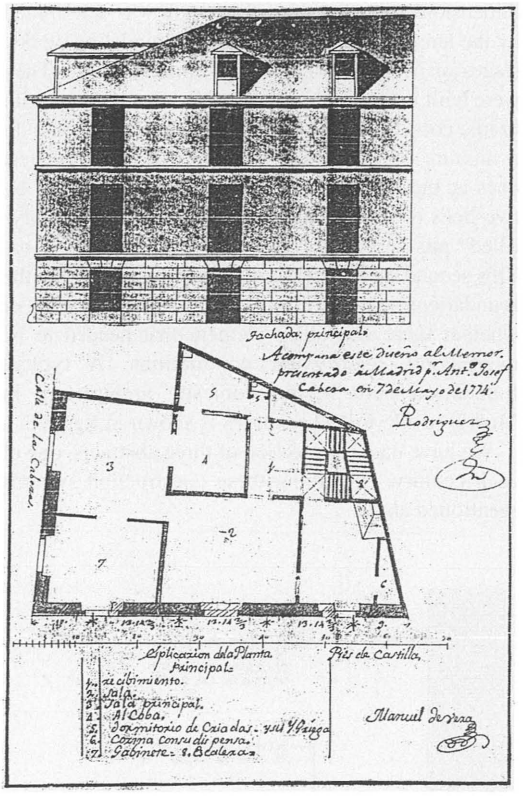


Figure 2
House built in Madrid in 1774. «Works licence application». AVS (1–48–10)

This paper presents a chronological historical approach using contemporary systems of measurement, typically castillian feet which were of an aproximately length of 28cm and castillian finger of around 1.74cm. This unity system was employed at least since the 16th century and it was not substituted until the end of the 19th century, when the international unity system, as we will see later on, mostly meters and centimetres, was generally introduced in construction systems. As mentioned in the previous lines, the attention will be focused on the documents contents, that is, the chronological approach following the date of the documents, the emplacement, work conditions and people involved in them, graphic information with the scale, and written information explaining the construction systems including the prices of the materials.

Construction systems: A general approach

The documental historical approach reveals a considerable information about the way of building houses that it can be hardly seen in the existing bibliography. The construction consisted of a structural wood framework both vertical and horizontal, usually called «entramado» placed over a foundation and a ground floor built both totally with masonry (brickwork or rough masonry work) and sometimes built also with stonework. Over it, there were placed a wood structural framework from the main floor or «cuarto principal» until the roof. The basic criterium to build them lyed in the width of the «carrera», that is, the beam placed horizontally in the walls, and from it they dimensioned the rest of the wood structural elements, decreasing in width as the house grew higher. The spaces left between the vertical and horizontal wood elements in walls (main walls, secondary walls, partywalls, etc) were filled with different materials, such as bricks, rough masonry work, sun-dried bricks, etc, and the spaces left between the horizontal wood structural elements in floors, with decreasing sections depending on the spans, were also solved with masonry.

This historical constructions systems made of wood were pecfectly regulated and controlled by the local government at least from the 17th century, and later on were slowly being substituted by masonry work as most by-laws of that time reflected. In many documents of the 18th century there are references about it but, in none of them, we have found that these new circumstances could make compulsory to build the houses only with brick. In the second half of the 19th century, it comence to appear certain concrete rules about this subject. The starting point of this subtitution process lies in the vertically structure, to be exact, in the main walls or façades which were the first ones built totally with brick. In what concerns the wood horizontal structures, it has to be pointed out that it was not until the end of the 19th century when they started being substituted by steel beams.

The main part of this paper, once advanced a general approach to the historical archives, is related to the study of the construction systems employed in Madrid domestic architecture of 17th to 19th centuries throughout the original documents. This study follows two lines: 1) the masonry construction systems and 2) the mixed structures, that is, the construction systems built of a wood structure and a masonry filling work.

Masonry construction systems

This part will analyse masonry structures built in Madrid in the 17th–19th centuries: 1) foundations; 2) caves; and 3) masonry walls including: a) main walls, b) «cítaras» or thin walls, c) party-walls and, d) partitions. To a better understanding of the written information analysed, we will bring to the most relevant abstracts of the documents transcribed in each section.

Foundations

The construction of foundations, as most contracts and records of works in the historical archives mentioned, always were a concern in the construction process. To classify the foundation types, we can analyse: dimensions, (depth, width, the length was determined by the length of main walls) laying foundation works, stages of filling the foundations, materials, etc. They were built in two different ways: 1) «Foundations with "zanja corrida" or a trench which was then filled with a mixture of stones and mortar placing the biggest ones at the bottom in different courses separated by two lines of bricks, and 2) foundations by "masonry-filled" pits and arches of stone or brick on the top». This second method was used when the site to lay the foundations was filled with demolished materials or whether there was some element that needed to be overpassed, also water conductions. A typical foundation built in the domestic architecture in Madrid in 17th to 19th centuries is shown in figure 3.

We have made a selection of three abstracts, one of each century, explaining these construction systems mentioned above

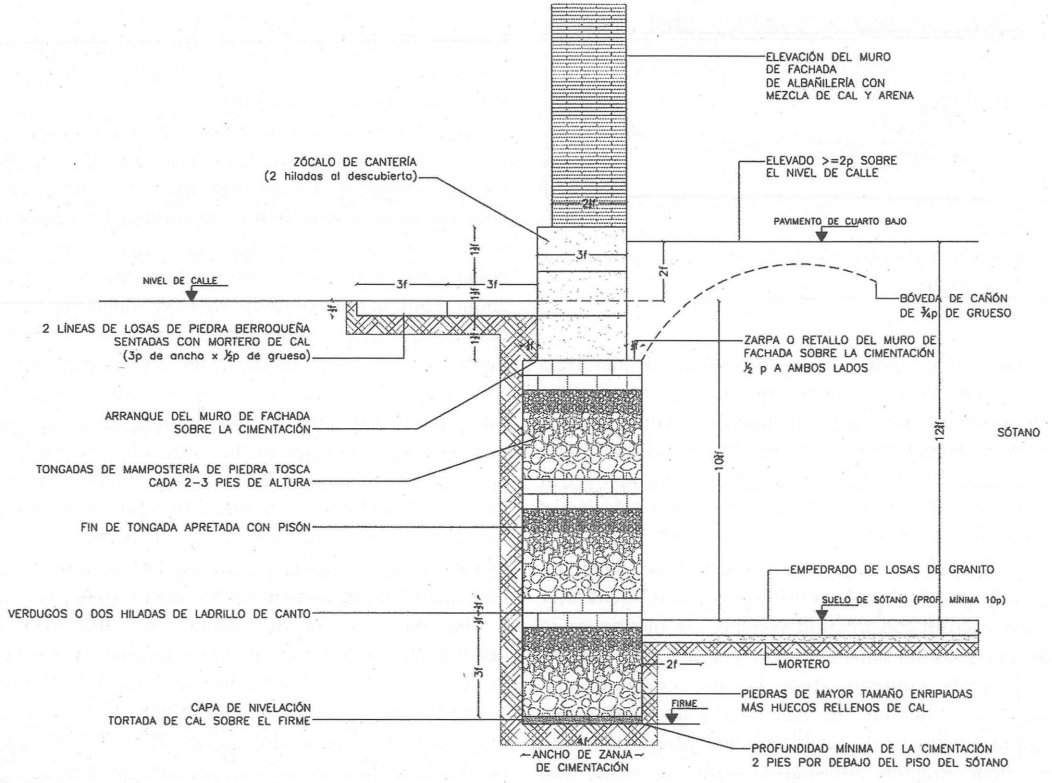


Figure 3
Typical foundation built in the domestic architecture in Madrid in 17th to 19th centuries

. . . que se a de abrir zanjas hasta lo firme medio pie mas anchas para rodapie que esto es mas ancho de lo que demuestra la planta y las a de maciçar con la mezla de cal dicha y areposada y de piedra de las canteras de San Ysidro y a de recivir toda la piedra que saliere de los redinos dejandolas a nibel del suelo o lladero quatro dedos mas baxas para el asiento de sillares y para elijir la mampostería. Que en el patio y patinejo a de sentar un sillar alrededor de media bara de lecho y media bara de alto y a esta altura, an de quedar todos los cimientos adbirtiendo que en el paño de la cavallerica los que caen del los a de labrar por de fuera con piedra pedernal de la marjen y por de dentro como los de demas los a de enrassar y enrassados todos a nibel y encima a de elegir verdugos y pilares adbirtiendo que el patio y patinejo y lo que falta de elejir en la calle todo a de ser de albañilería . . . Contract of work of a house built in C/ San Miguel. AHP N1 10.849 (1669).

. . . Se ha de vaziar el vano de los sotanos y gruessos de paredes a la profundidad de diez pies y quarto desde el pisso de la calle continuando las zanjas de otras paredes con un pie de zarpa exteriormente, y en lo ynterior, medio pie que es una de zócalo al cuerpo del cuarto vajo, y dos pies mas profundo que el pavimento de otros. Que hallado el firme y puesto à nibel se haian de mazizar las zanjas con mampostería vien travada de buena piedra pedernal, con su mezcla de cal correspondiente enrrassando de tres en tres pies y hechando à cada enrrasse sus dos yladas de canto de ladrillo de la mejor calidad levantando las paredes en la misma conformadas excepto la que hunde los dos sotanos que ha de ser de buena fábrica de alvañilería . . . AVS. 1–46–3 (1747).

. . . Los cimientos han de construirse de piedra pedernal con mezcla de cal y arena; sobre terreno firme, dándole cuatro pies de grueso hasta medio pie mas bajo que el nivel del piso de la calle, en donde retallándose medio pie de cada lado se sentará el zócalo de cantería de tres pies de altura lo menos con su tizon correspondiente, resultando dos hiladas descubiertas en el punto más elevado de la calle, continuando á nivel hasta el mas bajo, sin que falten estos en ningun punto de la fachada . . . AVS 1–114–26 (1838).

Cellars

Historical houses built in Madrid, principally those placed in main streets, often had stores in the ground floor and cellars or undergrounds under them. They were masonry walls built only with brick or with «mampostería» around 3.0–4.0 feet width (84 cm) and then covered with brick vaults with the bricks placed radially so they made the floors of the above stores. Both were comunicated by staircases or even provisional stairs. In general they were only built in the first «crujía» facing the main façade where they placed windows, also called «lumbreras» or «troneras» to light and ventilate the cellars.

En las tres tiendas, se pondran dos peldaños en la entrada de cada una de piedra con sus troneras para la luz, y ventilazion de los sotanos, y en ellas se pondran tres postigos nuebos enrrasados de ordinario, con un quarteron en cada uno con su varilla envevida, y el tercero peldaño de ellas, sera la peana del cerco . . . AHP N1 16.455 (1760).

Masonry walls: analysis of the structural composition

One of the main parts of this paper is related to the construction of historical masonry walls, that is, the vertical structural organisation of Madrid domestic architecture. As we will see along this part of the study, they were built with masonry, consisting of brick work only, or by mixing a vertical and a horizontal structure of wood and filling the spaces between them with rough masonry. The foundations were built to a height of 1.5–4.0 feet over the street level and were leveled with mortar, so that the walls defining the general vertical structure could be built above. From the very early documents the construction of walls, although very shematic in the first ones analysed, is mentioned. As we can see next in a document from the early years of the 17th centuries, although very scant in its graphic plan, reveals a quite detailed written information, about: material prices, masonry works, wood structural elements employed, etc, if compared with those of the same period of time. In the figure 4 is shown a contract of work of a house built in Madrid in 1636.

Primeramente cada tapia de manpostería de piedra de Caramanchel de cinquenta pies quadrados por prezio de quarenta y seis reales. Cada tapia de zitara vista de albañileria cuadrado por prezio de 60 maravedies. Cada pie de tavique de forja de todos los que vubiere en la obra 30 maravedies. Cada tapia de jaarro de zinquenta pies superfiziales por onze reales. Cada tapia de solado de zinquenta pies superfiziales por diez reales. Cada tapia de blanqueo a toda costa azeite yeso y paños por tres vellones y medio . . . N1 7055 (1636). Contract of work.

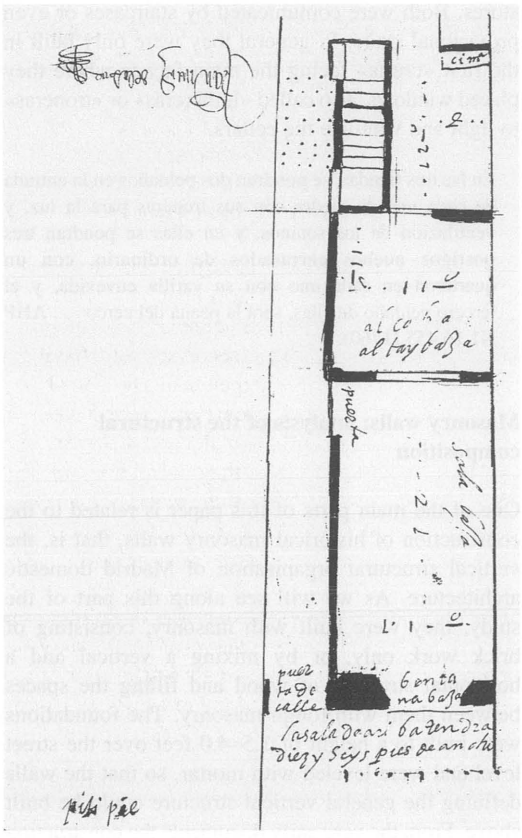


Figure 4
House built in Madrid in 1636. Contract of work, AHP. N1 7055

Masonry walls can be classified in four groups: 1) main walls, 2) «traviesa», thin or secondary walls, 3) party-walls, all structural walls, and 4) partitions, with no structural function but only a partition role.

1) Thick walls, main walls or façade walls:

The main walls were built in the main «crujías», that is, they were located in the main façades, in the internal walls following the direction of façades and in the interior court walls. Historically façades in Madrid were mainly built in two different ways: 1) Structural wood-framed walls which were traditionally built from 17th to the middle of the 19th century that will be studied in the next section, and 2) masonry façades walls which were built along these three centuries but, from the mid-19th century until today the exclusive ones. These walls were mainly built in two different ways: a) with a brickwork using bricks of (1 foot × 3/4 foot × 2 fingers), (3/4 foot × 3/4 foot × 2 fingers) and (1/2 foot × 3/4 foot × 2 fingers) and a mortar of lime and sand making a resultant width of (3.0, 2 3/4, 2 1/2, 2 1/4) feet (63–84 cm), and b) with masonry pillars and brick courses and filling them with rough masonry filling with a resultant width of (2 1/2–2) feet. Both of them were then finished wether as masonry exposed, as it is shown in figure 5, or with an external mortar and over it a madrilennian revoque. These main structural walls usually decreased in section as the façade wall grew higher. As it can be seen next, the wall inicial width was 3.0 feet and this section was reduced a quarter of a foot each upper floor until the last one which had 2 1/2 feet width.

> sobre el referido zócalo y con el mismo grueso de tres pies seguirá de fábrica de ladrillo y mezcla de cal y arena el cuerpo bajo hasta la imposta del piso principal y de la misma fabrica en todas sus alturas, siendo los arcos de puertas y ventanas del propio material sin entramado alguno ni humbrales de madera, retallándose un cuarto de pie por lo interior de cada piso de los siguientes, de forma que resulte el último de dos pies y medio para el asiento del alero . . . AVS 1–114–26 (1838).

In the next house repairing contract they alert not to demolish these main walls and neither to open a recess in it, excepting the external doors for the stores built at street level.

> Que en dicho reparo y obra nueva no se â de hazer rompimiento ni derribo en las Paredes Maestras de las dos ligneas ynterior ni esterior de circunvalacion de angulo agudo que forma la dicha casa escepto la abertura de las dos puertas para las tiendas y rejas de los entresuelos quedando firme el zimiento en la fondometria. Que dicha obra segun su plan â de empezar por la altimetria para quedar defendida antes que rompan las aguas ynvernizas. Que asta estar concluida la primer obra de la altimetria no se á de hazer derribos ni rompimientos para la segunda y tercera en los descensos . . . House repairing contract. AHP N1 16.968 (1745).

Madrid by-laws obliged to keep certain measurements for the balcons depending on the street they faced and the heigth of the floor, that is,

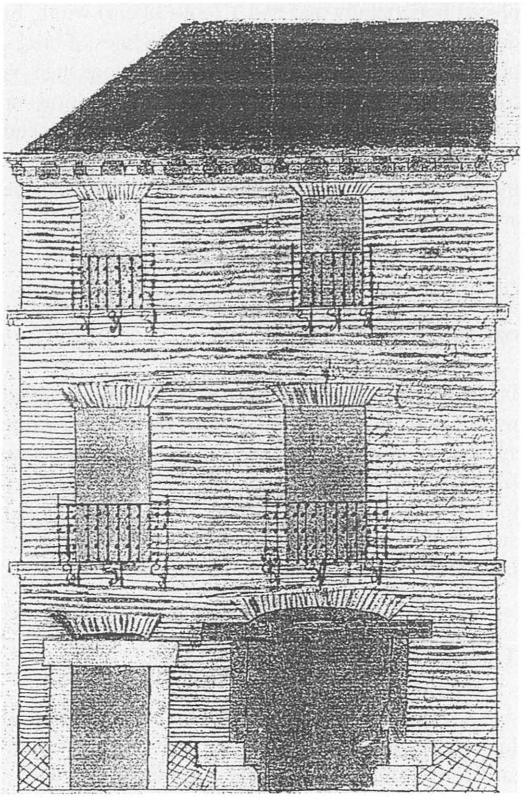


Figure 5
House built in Madrid in 1692 in masonry left exposed. AVS 1–10–44

decreasing from 1.50 feet in the main floor to only 0.50 in the third floor; they also regulated the doors at street level, the sidewalks and the finish work in the façades. The next abstract of a 19th century document refers to it.

> Los balcones en el caso de ser voladizos tendrán lo mas pie y medio los del piso principal, uno los del segundo, y medio los del tercero, dandoles de altura tres pies y tres cuartos, y el intervalo de los balaustres seis dedos, dejando recibidos las patillas en el grueso de la pared un pie, y mas de otro separados del vivo de la luz de las ventanas. En las puertas no habrá batiente ni peldaño que salga del filo esterior de las fachadas, para que no impidan el tránsito público, debiendo abrir aquellas hacia lo interior de la posesion. En la acera se sentarán losas de piedra berroqueña de medio pie de grueso y cuatro de salida, ciñéndola con el empedrado, labrada toda á moda con punta tirada bajo de un arrasante y sentada con mortero de cal, sin que en ellas puedan abrirse lumbreras orizontales á los sótanos, debiendo colocarse estas en las mochetas de las puertas, ó verticales á los demás huecos de ventanas; y por último se rebocarán las fachadas decentemente con arreglo á un buen orden de construcción . . . AVS 1–114–26 (1838)

2) Thin walls, «cítaras» or «tabicones»

This second part of the classification of masonry structural walls built in Madrid houses of the 17th to the 19th centuries, also called «cítaras» or «tabicones» (or thick partitions), «were secondary or «traviesa» walls that cut main walls perpendicularly. They had a width of $^3/_4$–1 foot (21–28 cm) and were located in interior court walls, interior walls and staircases. As in the preceeding section, they were built in two different ways, that is: 1) thin walls, «cítaras» or «tabicones» made with a wooden vertical and horizontal structure and filled with masonry work which will be studied in the next section, and 2) masonry thin walls. This second way of building the «cítaras» where, in general, the resultant width of the wall dependant on the position of bricks. The bricks most commonly used were those of (1f × $^3/_4$f × 2 fg), ($^3/_4$f × $^3/_4$f × 2 fg) and (2 f × $^3/_4$f × 2 fg).

3) Party-walls

The main structural fonction of the party-walls was the lateral or back separation of neighbouring houses. They had a width of $^3/_4$–1 foot (21–28 cm). Clerks of works used to build them perpendicular to main walls and to the rear of houses. As mentioned previously, the historical presence of party-walls was also registered in the different contracts of works, records and by-laws in Madrid. After the great fire of the Plaza Mayor de Madrid took place in 1790, Villanueva asked the local government of Madrid to outlaw building partywalls with wood and to encourage raising them only in brick. At the end of 19th century and in the construction of new zones of Madrid, Madrid laws stipulated that at least every third house should have a partywall made totally with brickwork, rising at least a metre over the highest part of the roof. Nonetheless this was not always respected. As with the main walls discussed previously, the vertical section of masonry party walls also decreased with height, being reduced by

around 1/4 feet in width at each floor. In this way party-walls had a typical width of 3.25 feet at the ground floor, 3.0 feet at the main floor, and so on until the roof.

4) Partitions

As mentioned before, partitions, the fourth group of masonry walls studied in this paper, divided the floors into usable spaces and did not have a structural function. From a structural point of view, they were held up by the wooden walls and were therefore built as thin as possible to reduce their weight. They were built in two different ways and their thickness varied in each case: 1) wood framework partitions filled with masonry, analysed in the next section, and 2) Masonry partitions built as follows: a) principal partitions or («tabicón»), in which the bricks were placed horizontally and had 1 foot (28 cm) width, b) double partition or («sordo») with two lines of bricks placed vertically and with a width of more than $^1/_2$ foot (8 fingers or 14 cm), and c) simple partitions or («panderete») with one line of bricks placed vertically and 4–8 fingers (7–14 cm) width. All these masonry walls studied in the previous lines can be seen in figure 6.

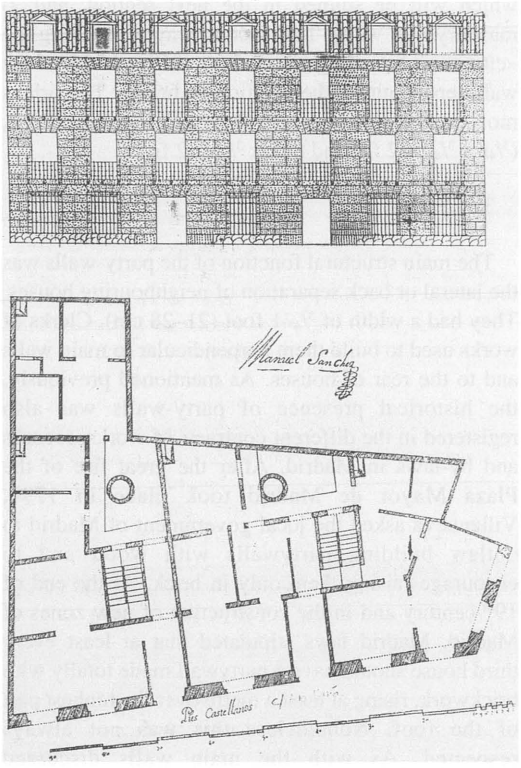


Figure 6
Masonry walls. AVS (1–84–16) 1742

Timber construction systems: structural organization

In some previous papers have been fully detailed written and graphically the most commun contructive systems employed in Madrid domestic architecture from 17th to 19th centuries. In the next lines we will try to make a general revision of the main timber structural organization of this kind of buildings for a later better understanding of the documents analysed.

Timber elements

As it has been mentioned before, timber framed historical constructions were built with a wood structural frame (vertical and horizontal) and with a rough masonry filling. The most common wood elements employed in Madrid in 17th–19th centuries were named according to their measures (length, width, height) and price (Ardemans, 1719). They are classified in separate groups according to the role they played in construction systems: 1) timber structural elements (used whether vertically or horizontally): beams, small beams or «viguetas» and «maderos», they were employed to build the main structure of walls, floors and roofs and they are classified according to the names and main dimensions ordered as the section and length proportionally decreases in Table 1 and 2) non-structural timber elements: «rastreles» and planks mainly used to cover floors and roofs, they can be considered as a third and fourth wooden level in domestic construction systems used in Madrid. As in the previous table, they are classified according to their dimensions (length, width and height) in Table 2. These wood elements, structural and non-structural, were mostly joined with nails of different types according to their lengths.

Table 1
Timber structural elements

	NAME	DIMENSIONS Length (feet)	Height (feet/fg)	Width (feet/fg)	
BEAMS	Half vara beam	< 30 > 30	1 ½ feet	1	□
	Foot and a quarter beam	< 30 > 30	1 1/4 feet	1	□
	One third by one fourth beam	< 30 > 38	1feet	3/4	□
	One fourth by one sixth beam	22-30 > 30	3/4 feet	½	▮
	22-feet 'vigueta'	22	3/4	½	▮
	Half 'vigueta' (12 f)	12			▮
MADEROS	Madero of a 6	18	11 ½ fg	8 fg	▮
	Madero of a 8	16	9 fg	7 fg	▪
	Madero of a 10 double	14	7fg	5 fg	-

Table 2
Timber non-structural elements

	NAME		DIMENSIONS Length (Feet)	Width (Fingers)	Height (Fingers)	
RASTREL	'Alfargía' of 12 feet		12	5	7	-
	'Alfargía' of 9 feet		9			-
PLANKS	'Tablón'		-	3	-	
	14 feet	Gordo's plank	14	18	2 1/2	—
	9 feet		9			—
	7 feet		7			—
	12 feet portada's plank		12	24	2	—
	14 feet	Chilla's plank	14	16	2	—
	9 feet		9			—
	7 feet		7			—
	Ripia's plank		4	8/3	4 lines	

As we can see in the next abstract from the early years of the 17th centuries, in the contracts of works all these wood elements were perfectly typified following the tables previously shown.

> Cada bigeta de beinte y tres asta beinte y cuatro que es lo que a de llevar la sala baja y alta y esto se entiende cargando en el pilar de la medianería con su bobedilla acabada en toda perfezion por precio de quarenta y quatros. Cada madero de a seis de la misma manera rematado por prezio de veinte y ocho reales. Cada madero de a ocho de la misma manera rematado y que tenga desde doze pies arriba sin no los tubiere rezudiendolos a ellos por veinte reales. Cada pie de viga de terzia y quarta labrado y sentado por tres reales y medio. Cada pie de viga de quarta y sesma labrado y sentado por sesenta maravedies. Cada viga de tejado que sera de quarta y sesma con bentaja toscas sentadas por prezio de treinta reales. Cada tabla de una quarta de ancho clabada por sesenta maravedis. Cada tramo de madera de a seis cuatro al tramo entablado con tablas de carreta por prezio de beinte y dos reales que es cada tramo ocho ducados. Cada tramo de madera de a ocho cinco al tramo entablado de la misma tabla cada madero de doze reales que es cada tramo sesenta reales. Cada peldaño de escalera de una bara de grueso perdidas las zancas y mesillas por prezio de catorze reales . . . Contract of work. AHP N1 7055 (1636).

The elevation of the neccesary provisional structure to build the house, the scaffolfs, were also registred in some contracts of works indicating the main sections of the wood elements, the way of placing them, and also some instruccions to follow, such as not to leave too many bricks on them, to prevent possible accidents

> . . . En la construcción de andamios de las fachadas de esta casa, se observará que las almas sean de sesmas colocadas en medio de los huecos, á escepcion de las de los estremos que estarán á la línea de los muros medianeros para que por este medio no resulten mechinales en la fábrica; los puentes serán de maderos de á seis y los tablones de buena calidad, sin nudos saltadizos, poniendo tres por lo menos en el ancho de cada andamiada, no consintiendo el Arquitecto se carguen con mucho ladrillo, y para evitar todo motivo de desgracia, se pondrán maderos de á ocho ú de á diez entre las almas que sirvan de antepecho ú barandillas; elevados de los tablones cuatro pies menos cuarto; redoblando este cuidado en donde se coloque el pescante, el que será formado con toda solidez, y los andamios interiores cuidará el profesor se hagan segun arte, con la idea de precaver la ocurrencia de una desgracia. AVS 1–114–26 (1838).

Construction systems built with timber

The main constructive systems built with timber in the domestic architecture of 17th–19th centuries in

Madrid were: 1) timber walls, 2) wooden floors, and 3) wooden roofs.

1) Timber walls

This section of the domestic architecture of 17th–19th centuries of Madrid is separated in five groups: 1) main walls, 2) «traviesa», thin or secondary walls, 3) party-walls, all of them structural walls, 4) partitions (no structural function), and 5) «corralas» or corridor houses. As it has been said in the previous section, walls were not only built with masonry but also with a mixed structure.

- Timber-framed façade walls. Madrid façade walls from the 17th century until the end of the 18th century were built with a timber frame which supported wood and masonry floors, and was filled with brick, rubble, plaster, adobe, etc. They were built on a masonry first level (ground or store floor). This constructive system continued from the main floor until the roof. Then the façades could be left exposed or covered with a finish of mortar and plaster, or «madrilenian revoque». Typically the houses had four or five floors over the cellars: ground floor, main floor, second, third and attics (roofs), depending on the width of the street they face. In figure 7 is shown a house built in Madrid in 1747.

. . . Que sobre las medias varas de las fachadas continuando su elevacion se hayan de sentar los pies derechos, y carreras de tercia para entramarla por el alto del cuarto principal disminuyendo las paredes por la parte ynterior hasta quedarse en pie y medio, y se devera fabricar eligiendo los vanos de ventanas de buena fabrica de Alvañilería . . .

. . . Que se haya de levantar el alto del quarto segundo con sus entramados en las fachadas de madera de tercias del mismo grueso de pie y medio de buena fabrica de Alvañilería, y en lo ynterior de sesmas y taviques de yesso y cascote guardando los plomos de los vanos como muestra el alzado . . .

. . . Que en la elevación del quarto tercero se haya de continuar con los mismos entramados de tercia con carreras y puenttes de la misma calidad de pie y medio, del propio grueso en las fachadas, y de la misma fabrica de alvañilería dejando sus vanos de ventanas como expresa el alzado, y sentando las soleras ynteriores al nivel de las exteriores . . . AVS. 1–46–3 (1747).

In 1790, a great fire ocurred in the Plaza Mayor of Madrid, where more than 50 houses burned, and was only stopped at a house totally built with masonry. This

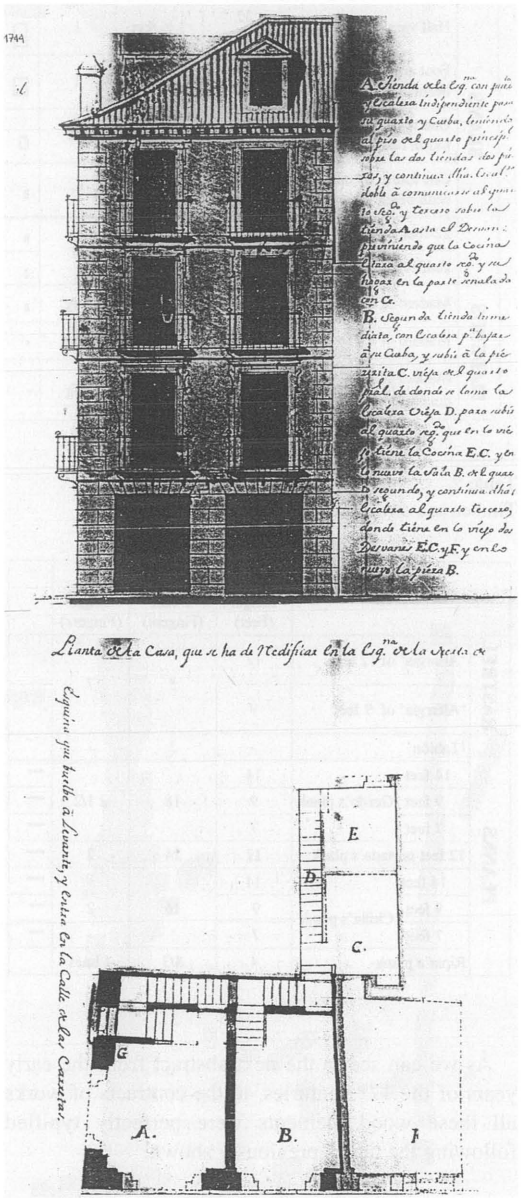


Figure 7
House built in the Puerta del Sol in 1747. AVS. 1–46–3

occurrence, as well as the fire-prone constructive systems usually employed in Madrid houses, caused Juan de Villanueva [3] to advise building façades totally of masonry in Madrid, and to not allow wooden elements. In the following century most of the houses were built from the foundation to the eaves of the roof in masonry, and leaving wood framed construction only for thin walls, party-walls, partitions and «corralas» walls.

- Timber-framed thin walls, «cítaras» or «tabicones». Villanueva in his book «Arte de albañilería» explains these two different building methods. He suggests to build these walls only with masonry, and not wood, but in practice wood structural walls continued to be built until the start of the 20th century. The section of the wood elements used in the «cítaras» also decreased as the house grew higher. That is, the ground floor used beams of tercia, the main floor used beams of sesma, the second floor beams of «maderos de a 6», the third floor beams of «maderos de a 8», and so on as in the contract of work shown in figure 8.

In the two next abstracts we refer to it.

que el salon alto se compone de una zítara a la parte de la calle y un tabique dentro. La citara nezessita mas cuerpo y esta se a de acompañar y crezer echando solera abaxo y carrera arriva de quarta y sesma labrada y nudillos que abrazen solera y lo que se anide y pies derechos y puentes en las bentanas y riostras dando de gruesso a esta pared todo el largo de la calle de dos pie y medio porque defienda en berano del mediodía y lo mismo a de ser la pared que cay al oriente por su defenssa ase de maçiçar el pie y medio de dicha citara de yeso y cascote echando gatos que una uno con otro baxando lo que le toca a dicha citara . . . AHP N1 10.849 (1669).

Tabiques principales, sobre que han de cargar los suelos, y el de la escalera, que cae al Patio, han de ser sus carreras de madera de terzia con sus respectibos entramados, hasta recivir el suelo de los desbanes, y de alli arriba seran de vigueta, y sesma, sacando sus cepas sobre el firme de mamposteria, y sobre ellas sus buenas vasas de piedra verroqueña; y los intermedios la misma mampostería de media bara de grueso hasta la superficie, y desde alli hasta enrrasar con dichas vasas, sera su citara de ladrillo de un pie de grueso. AHP N1 16.455 (1760).

In the contracts of works, they also include the construction of staircases timber walls.

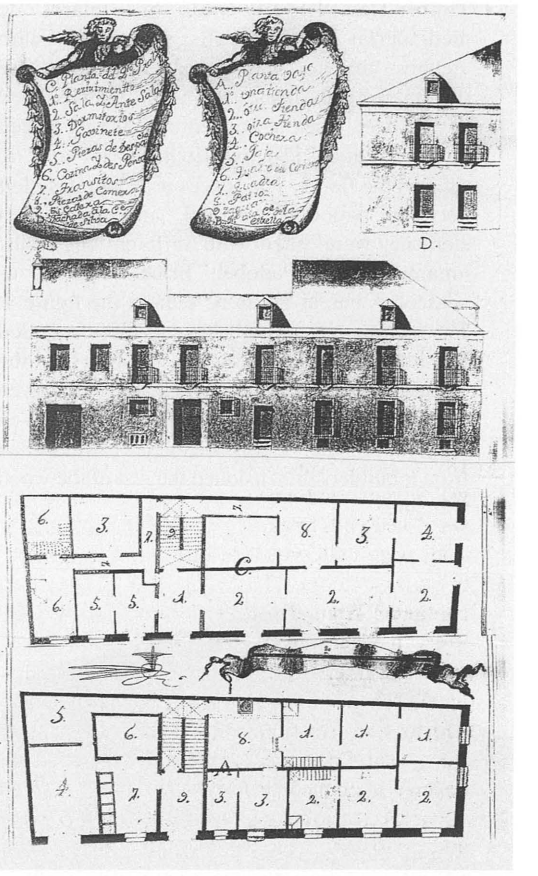


Figure 8
House built with timber-framed walls: main walls, thin walls, timber partywalls and timber partitions. AHP N1 10.849 (1669)

y en lo ynterior se deveran entramar los taviques para formar las escaleras, vajo de sesma, y el de la zitara que hunde vajo de tercia, y los peldaños de las escaleras han de ser de viga de pie y quarto desde el primer sotano hasta el ultimo del desvan con sus entradas suficientes en las paredes y taviques para su seguridad. Y por que al pisso del quarto principal empieza la escalera que tiene su entrada por la Calle de las Carretas de otra forma que atajo y se reduze a yda y buelta, y carga sobre el suelo un tavique que para recivirle se pondra una tercia donde cargue la division, y continuará esta por toda la altura como expressa el alzado . . . AVS 1–46–3 (1747)

- Timber-framed party-walls or «telares de medianería». These walls were built with «telares» that is a main wood vertical structure surrounded with ropes or «tomiza» and separated by 5–6 feet. Then a wooden capital was placed on the columns and over it the beam used to support the floors. The spaces or «cuarteles» left between wooden vertical and horizontal elements were filled with different materials: «mampostería», adobe, brick, rubble or «cascote», etc. as it can be seen in the figure 9. The section of the wood elements also decreased as the house grew higher, similar to the construction of façades. The name usually given to each wood structural framework, depended on the width of the wooden element «carrera» and from it builders dimensioned the rest of the wood structure.

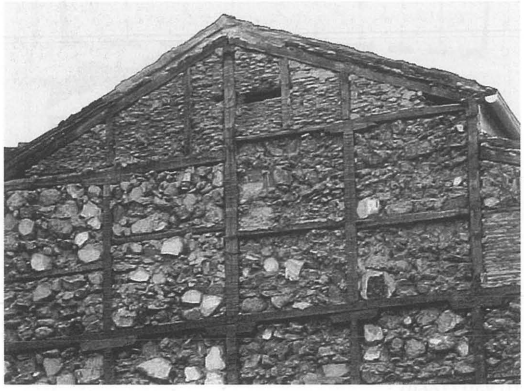


Figure 9
Timber-framed partywall or «telar de medianería». C/ Ventura de la Vega

las medianerías con sus vasas y carrera de vigueta, â sesma entramadas de sus respectibas maderas . . . AHP N1 16.455 (1760).

- Timber-framed partitions. When building framed wood partitions, builders often tried to support them from perpendicular walls so as not to add too much weight on the floors. Lightweight fill materials such as adobe, brick, and small rubble, but most often with plaster. Their dimensions varied between 1, 3/4, 1/2, and 1/4 foot. They were usually built in two ways: 1) supported directly on the floors employing mainly «maderos de a 6», «maderos de a 8» or de» maderos de a 10' and with a filling of bricks, plaster or rubble or 2) with a hung construction supported on a beam spanning between perpendicular walls and using «maderos de a 8» and «de a 10» and filling them only with bricks or plaster. A third type was rarely used built with adobe (rubble and plaster).

Los tabiques de quarto principal (de las divisiones) algunos de ellos, como son los que cargan en los vanos, se haran colgados, que estos bien echos, quanto mas delgados, son mejores, pero a donde no vea nezesario esta prevencion, se haran de medio pie de grueso, y lo mismo en los desbanes; para demas tabiques de divisiones de lo bajo, de forja de madera de a diez su entramado con sus vasas ordinarias, cepaes y citaras . . . AHP N1 16.455 (1760).

- «Corralas» walls. The final type of walls that will be studied in this paper are the «corralas» walls, made of open wooden framing which supported the galleries around the interior courtyard. In «corralas» houses, a series of corridors are supported by an open framework of vertical and horizontal timber elements. These types of walls were also called «courts entramados». These structural walls in corridor houses had around 3/4–1 foot (21–28cm) width.

Wooden floors

Historically floors were built in wood until the end of 19th century, when they began being built with steel beams. From a structural point of view, the constructive system employed was a horizontal structural frame of timber beams supported in main two-layered or timber-framed façade walls covering main spans of floors. Structural floors organisation varied depending on the spans; in buildings of only one bay (span), for very small distances (3.0–4.0) meters, the beams were directly supported on the masonry or timber-framed walls; when the spans were of medium length, that is, (5.0–7.0) meters, the beams were placed perpendicular to main walls and

small beams following the direction of main walls; in those houses with large spans, that is, (8.0–9.0) meters, it was recommended to build the house with two bays (spans) following the timber beams the longitudinal direction. The perimetral supports were solved whether in the lateral party-walls or in the façade and back court walls. The central supports were solved with pillars or with secondary walls or «cítaras». Even if the spans were in every floor the same, the section of the timber framed floors could vary depending on the height of the house: main floor, second floor, third floor, etc.

They were basically built in two different ways according to the separation of beams: 1) «hueco por macizo»; and 2) «hueco wider than macizo». The spaces left between them were filled with rough masonry work or different timber planks nailed together. Next we will explain each of them.

Timber floors constructive system solution «Hueco por macizo»: This solution consisted of separating the beams by around the same width as the width of the beam itself. This distance could vary (5.0–11.5) fingers. The most common timber sections used in this floor solution were the «maderos de a 6», «maderos de a 8» and «maderos de a 10». The spaces left between them were solved whether: 1) with timber planks or «enlistonados», 2) with bricks which were placed directly on the beams and the under part was left uncovered or with a false roof; and 3) filled with rough masonry work. In figure 10 we can see a photograph of it.

> hechando los suelos del quarto segundo en la pieza del angulo de madera de a ocho cargando las cavezas en la fachada de levante y en la pieza inmediata viguetas de a veinte y dos pies que carguen en la fachada del Norte . . .
> . . . hechando los suelos del quarto tercero en la pieza del angulo de la misma madera de à ocho y al contrario del antecedente del quarto segundo cargando las cavezas en la fachada del Norte, y en la ynmediata de viguetas en la misma conformidad . . .
> . . . hechando sus suelos de desvanes en la conformidad que los del quarto segundo . . . AVS 1–46–3. (1747).

Timber floor constructive system «Hueco-macizo». This solution consisted of separating the beams a distance wider than the section of the beam itself and around (1.5–3.0) feet width. The most common timber sections used in this floor solution



Figure 10
Timber floors constructive system solution «Hueco por macizo». C/ Relatores

are third and fouth beam, fourth and sixth beam, «vigueta», «madero de a 6» and «madero de a 8». As in the preceeding section, the spaces left between them were solved in two different ways: 1) with planks and 2) filling the spaces left with rough masonry or «cuajado».

The introduction of steel beams for floors in the domestic architecture in Madrid did not appear until the end of 19th century. At that time the timber floors were substituted by floors with double T beams separated by approximately one meter and with the spaces left between them filled with ceramic «botes» and black plaster. This structure was supported on the main walls by steel squares and clamps. In a previous paper (González and Aroca, 2000) we have shown the comparative advantage prices for the steel and the underlying logic of the substitution.

Roofs

The construction of roofs typically employed in historical domestic architecture in Madrid in 17th–19th centuries by studing the stages and their components: 1) roof wooden frames, main structure or «armadura» and roof wooden secondary structure or «pares», 2) «entablados» or floorboards made of «rastreles» and planks in a similar way as they built floors and, 3) covering elements.

Roof wooden frames (main structure and secondary structure). Roofs were built with a main wooden structural frame of beams and a secondary structural level of «pares» or small beams placed and nailed perpendicular to the first ones. They were built in different ways: a) «a la molinera», this was the usual type for roofs built to courts or «corralas». The «pares» or small beams are perpendicularly supported on main walls and over them they placed planks before placing the roof tiles going always only towards one direction; b) «par e hilera», in houses of two bays (spans) where over a central wall they placed very short pieces of wood named «enanos» and over them a «hilera» which served to build the ridge from where started the «pares» or small beams going to meet the beams placed on the façades and backwalls. They were then covered with planks placed paralell to the supports,

> que sentara cada pie de estribo i ylera de vigueta de quarta y sesma uno con otro por precio de dos reales y medio sentando los estribos a cola como es costumbre. Que sentara cada pie de vigeta de quarta y sesma en armadura por precio de sesenta maravedíes. Y si fueren vigetas que pasen de veinte y tres pies cada pie en armadura por precio de dos reales y un quartillo. Que sentara cada madero de a diez doblado en armadura por diez y seis reales. Que sentara cada madero de a ocho en armadura por veinte y dos reales. Que sentara cada pie de estribo de madera de a ocho sentado en caxas por precio de dos reales.. AHP N1 10.849. C/ San Miguel. (1669).

The third method, c) «par y picadero», is nearly the same type as the first one but, in this case, the «pares» are placed over the beams named «soleras» and «carreras», with cuts in the central piece named «picadero».

> . . . Que sobre otro suelo se haian de sentar sus aleros de sesma vien clavados contra los maderos del suelo que sirven de tirantes y sobre otros extremos en el angulo se ha de sentar por lima una tercia con un picadero donde se han de assegurar las pendolas y pares que seran de sesmas bien clavadas, y en ella y en sus cavios dejando las buardillas con sus antepechos de forma que demuestra el alzado y deveran ser de buena madera y conformacion todo entablado de chilla, y bien clavado y tejado convasisco à lomo cerrado con voquillas de yesso respaldadas y Cavalletes . . . AVS. 1–46–3. (1747).

2) Floorboards or «entablados»: «rastreles» and planks. Once this frame or main structure was raised, they placed small longitudinal pieces of wood or «rastreles» and planks nailed on them (often mentioned to be of «ripia»: 4 feet × 8/3 fg × 4 lines). Nonetheless Villanueva suggests to place bricks on them or «bovedillas» between them adding mortar in the under part to avoid the frequent and undesired fires that threatened Madrid. In the mid-19th century it was mentioned, as a posibility in the new by-laws of Madrid (1862), to build them with iron but, in fact, iron was not used until the next century.

3) Covering elements: roof tiles. After placing the planks, the most common and almost the only element used to cover the main wooden roof structure were the roof tiles. Nevertheless, for those new houses that could be built in the new «Ensanche» of Madrid, the contemporary by-laws mentioned a great set of other possibilities, such as metal plates of steel, lead or zinc.

Conclusions

This approach verified the uniformity of the structural construction systems of masonry: brick work and wood framed mixed with rough masonry used to build the domestic architecture in Madrid during more than three centuries. Once the main characteristics of the basic contruction elements are known, including the materials, dimensions and methods of construction, a structural analysis can be carried out to guide future interventions (if neccesary).

Note

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Typological observations on tapia walls in the area of Seville. 11th-19th centuries

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In spite of the advances that, during the last two decades, have been taking place in the field of research on local building techniques, especially in the andalusi period, the analysis of the wall typologies (their fabrics, materials and execution) has raised little interest when compared to the one awoken by ornamental and spatial studies. This may be due to the lack of archaeological excavations that could help to add new information. In fact, the general approaches to the topic are not frequent. (Pavon 1998:569 y ss) (López 1997)

The aim of this work is to make up for this lack concerning the tapia fabric by offering a first systematisations of the typologies corresponding to different historical periods, starting from the abundant data obtained during the archaeological excavation campaigns, especially the ones carried out in the Reales Alcázares of Seville since 1997. In any case, we are working with the conviction of the temporary character of the proposed classification that will therefore be always open, and of the necessity of completing the initial results in the future with the ones included in the previous and next excavation memories, in order to institute a typological analysis that allows archaeologists and historians a quick approach to the building fabrics. As it happens with all typological classifications, we want it to be open to possible alterations and additions and at the same time to be a true reflection of the existing data.

The typology that we are proposing is based on three premises so in every typology established in the classification three questions are analysed. The first is the compositive one, distinguishing among common or simple tapia, chained tapia and mixed fabric tapia. The common or simple tapia is the one where the formwork crates are superposed without any vertical element articulating them. The chained tapia consists of males (made of brick or stone) with a variation of recess in the chains depending on the corresponding chronology. The mixed fabric tapia is that one in which, not having a direct superposition on the formwork crates, the latter are separated by a course or by a series of courses made of another material. (Graciani 2001)

As a second premise we establish the dominant aggregate, and according to this there are two types of tapia: gravel tapia and ceramic fragments tapia which incorporates no natural aggregates but, on the contrary, crushing aggregates (bricks, fragments and remains of pots) that can be minute in some cases or quite big in others. The material composition is not only due to technical reasons but to the availability of material at the moment and to the functional requirements and ,therefore, to the consistency of the different fabrics. The last premise is the module of the mould or crate (always determined by its height) thus distinguishing between the short module tapia with a height of 0.80 m or lower and the high module tapia with a height between 0.85 and 0.95 m (probably equivalent to two mamuni elbows, of 47.14 cm each) and with a width of 2.25 and 2.50 m Any other feature that may appear in a tapia fabric can be merely

circumstantial. In any case, other data must be noted, for example those referred to boards, formwork needles, foundations, *calicastrado* and coating. (Tabales 2000)

This piece of work will be structured in five sections, following a chronological criteria:

1. The first tapia walls in Seville
2. The African tapia fabrics: the expansion and the almohad advances
3. The mudejar tapia walls
4. The tapia walls in the modern age
5. The tapia walls in the contemporary age

The first tapia walls in Seville

The oldest tapia walls detected so far in Seville have appeared in the Alcázar. In its walls dated in 914 clay and lime *emplecton* is used, following the Roman tradition custom that was kept in the later military architecture. There are references of this use in the stone city walls of emiral and caliphate cities such as Badajoz and Toledo. We also find it in the 11th century doors (Joaquín Romero Murube street).

The documentary sources insist on the use of tapia in the walls of the taifa period, which is not strange because, even though this technique had already been used from the emirate times in other locations, it is from the taifa period on when, due to the speed in the execution and the solidity of the resulting fabric, its use proliferates, especially in military constructions. This reality contrasts with the scarcity of remains that can be surely dated in the taifa period which, in any case, would be the oldest wooden formwork tapia (*tabiya tapia*) in the Alcázar.

The only tapia fabric which can be ascribed to the taifa period (although late) corresponds to the lower part of the East wall of the Precinct II (excavated in two points, La Alcubilla and La Muralla del Agua). This ascription is established especially by the associated ceramic material of the 11th century but also by the typological similarities between the tapia walls of the taifa and almoravid periods, being in the almohad period when the characteristics are especially defining.

They would be the only taifa remains because, as it has already been noted, the recent excavations in the south west stretch (Patio de las Doncellas and del Principe) of the walled Precinct III have shown that these stretches do not belong to the taifa period, thus questioning the traditionally accepted statements of Guerrero Lovillo about the taifa dating of the SW span, as part of the closing wall of the Al Mubarak Alcázar enlargement. In any case, they would be prealmohad, possibly almoravid.However, if we maintained the hypothesis of R. Manzano (Manzano 1995: 111), the tapia fabric of the Patio del Yeso (north and east walls) would belong to the taifa period.

As it has already been indicated and contrasted with the amount of documentary references, the certain information about taifa tapia walls is scarce, not only for the few remains conserved, but also because of some of the existing ones, their chronological sequence is not known for sure and in other cases because the limitations of the excavations carried out have not allowed to obtain data of some aspects such as the length or the thickness of the formwork crates that, according to Pavón Maldonado (Pavón 1998:613), depending on the dimensions of the wall mould plate, varied between 2.10 and 1.50 m.

Thus, we could say that the 11th century tapia, at least in the few types dated, show their basic differences in the composition, having, on the other hand, the three following characteristics in common. The two first of these give them the quality of common tapia: 1.-Lack of males and chaining in brick. 2.-Direct superposition of the formwork crates, without courses or series of courses between them.3.-Short module, i.e., short height (+ 0.80 m being 0.85 in the east wall and 0.75 in the Patio del Yeso). It is probable that these measurements derive from the use of the rassasi elbow (proper of the omeya sphere). So, starting from the existing data, we can establish two typologies.

Gravel common tapia fabric, of short superposed formwork crates

The tapia walls of this typology correspond to the east wall (excavated in La Alcubilla and in the lower wall of El Agua) and to the south enlargement of the Precinct III (drilling SE-VII, below the Alfonsí palace, in the passage that connects the Patio de la Danza with the tank of the Baños de Doña María, a span that corresponds to the southern stretch of the

Precinct II, thus belonging to the taifa period. It is a gravel tapia (a typology introduced in the taifa period) made of *zahorra* (fine gravel), orange clay and lime that it was also calicastrado (Figure 1).

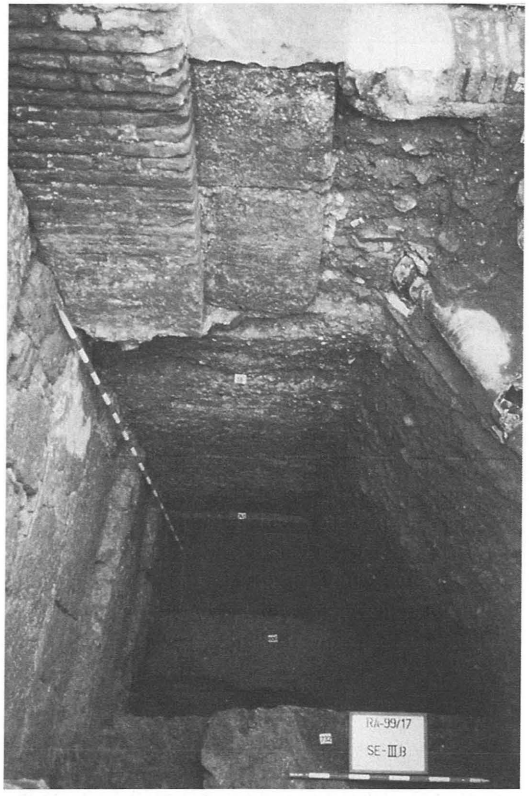


Figure 1
Stretch of the abadí tapia wall (middle of the 11th century), Muralla del Agua of the Alcázar of Seville

Common tapia fabric of minute rubble and short superposed formwork crates

This typology corresponds to the north and east walls of El Patio del Yeso, dated with reserves in the 11th century. This fabric has minute rubble as an aggregate, soil and lime as a conglomerate and ashes as an additive, not only as a result of the impurities generated in the burning process of the lime in the kiln, but also to act as a degreasing and to help the drying, thus giving it a higher porousness and sponginess to the fabric, that, as a result, loses quality. This is not strange if we think that the purpose of this fabric is a domestic, not a military one (Figure 2, table 1).



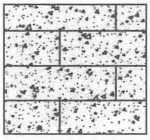
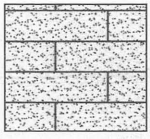
Figure 2
North stretch of the Palacio del Yeso, Alcázar of Seville. Probably abbadi. (11th century

The African tapia walls: The expansion and the almohad advances

Although the first samples found correspond to the beginning of the 10th century and more surely to the taifa period, most of the existing remains belong to the African period and, very especially, to the almohad one, dating it in a general way between the second half of the 12th century and the 13th century (García-Tapia and Cabeza 1995). It is precisely from the almohad period on when the construction of tapia fabrics proliferate at all levels: domestic, religious,

TAPIAL WALLS IN THE AREA OF SEVILLE
Cronological classification

table 1.
Identification of the main types of Sevillian tapial wall. 11th century

Cronology	Scheme	Module	Composition	Males	Formwork crates superposition	Foundations	Evidences
Abbadita 11th century		Formwork crate: 0'85×2'70×2'00 Formwork needles: 0'50 Boards: ---	Lime Clay Gravel Minute rubble Calicastrado	Lack of males	Direct superposition	Lintel in the second formwork crate. Lack of a differentiated foundation Lack of plinth.	East Lower Wall of the Alcázar (Patio de la Alcubilla): 11th century. Lower Wall of El Agua 11th century.
Abbadita 11th century		Formwork crate: 0'75×---×0'45 Formwork needles: 0'50 Boards: —	Sand Ash Lime Minute rubble	Lack of males	Direct superposition	-----	North and East Walls of el Patio del Yeso del Alcázar. ¿11th century?

public and, fundamentally- even over the stone construction, military. Consequently, there is a larger typological diversity in the tapia fabrics in this period. (Campos y Moreno 1988)

The novelties are two. The first one is that, from the second half of the 12th century the module of the tapia increases: it is close to 0.95 m of height (Valor 1991). The second one is that in the African period we find three variants of tapia depending on the compositive structure: the common or simple tapia, the chained tapia and the mixed one. There are well documented examples of the two first variants in the Alcázar of Seville. In any case, this means an important change with respect the preceding period in which all the existing examples belonged to a common typology. In all the cases that we will deal with below, except in one, the tapia formwork crates appear directly superposed one on top of the other; only in 2.2.3. one of the typologies corresponding to the 13th century, there will be a separation of one or two brick courses between the formwork crates which will mark a progressive tendency in the diminishing role of the tapia formwork crates in the fabric as a whole.

Common tapia walls

There have appeared common tapia walls corresponding both to the first half of the 12th century and to the second one, which evidences that this structural variant of the tapia wall, the classical one of preceding periods, is maintained. Examples corresponding to the three different typologies of the common tapia wall have been found. Only one of them is with a short crate (from the first half of the century). Of these typologies, only one is of gravel tapia, the two other ones are of rubble tapia, one of big ceramic pieces and the other one of minute pieces. The typologies are the following:

Common tapia fabric of big rubble with short superposed formwork crates

Formally, this typology is identical to the one that appeared in the north and east walls of the Patio del Yeso (1.2), both showing the following features: 1.–Lack of males and brick chaining. 2.–Direct

superposition of the formwork crates, without brick separating courses. 3.–Short module, i.e. short height (± 0.80 m being 0.75 in the Patio del Yeso and varying between 0.75 and 0.80 m high by 1.10 m long by 2 m wide) However, both differ in the dimensions of the crushing aggregates that have been incorporated and which consist of tiles, bricks and pieces of ceramic pots of a bigger size. An example of this typology are the remains found in the Alcázar of Seville, in the lower part (± 1.20 from the ground) of the wall that is at the back of the Patio del Principe, de la Galera and de la Cruz (sample 13) and which come out even with two towers. In this case it is a greyish tapia made of big rubble and abundant lime although to its composition natural aggregate (gravel) has to be added to the crushing one.

Common tapia fabric of minute rubble with high superposed formwork crates

This typology shows the following features: 1.–Lack of males and brick chaining. 2.–Direct superposition of the formwork crates, without separating brick courses. 3.–Short module, i.e., short height. Only one example of this typology has been found and it is dated in the end of the 12th century, precisely the fabric of the west wall of the Patio del Crucero of the Alcázar of Seville which shows the particularity of its width (±0.60 m.), evidently lower than the usual one (2.25–2.50 m.)

Common gravel tapia fabric with high superposed formwork crates

Of this typology we have remains of different periods (from the 11th century to the end of the 13th century) in three points of the SW angle of the Alcázar and following a chronological sequence are the following: a) below the Alfonsí palace in the passage that connects the Patio de la Danza with the tank of the Baños de Doña María a span corresponding the south stretch of Precinct II, from the taifa period (SE-VII); b). In the Patio del Principe and below the Palacio del Rey Pedro I there are some remains from the Precinct III corresponding to the middle of the 12th century which can be almoravid or almohad; c) a wall of the almohad palace of La Montería (end of the 13th century).

Even though they present the logical variants due to the different aim of the walls (palatine or defensive), they all maintain the following features: 1.–they are common tapia walls, without males; 2.–They are gravel tapia walls made of lime, clay and gravel (*zahorra* in the Patio del Principe). 3.–The formwork crates are of long module (0.95 × 2.25 × 2 . . .) and they superpose directly one on top of the other. The differences refer to density, formwork needles *and calicastrado*. In fact, logically, the stretches of wall, due to their defensive purpose, show a bigger density (0.95 × 2 × 2.20) than the palatine walls where it is of 0.50 m The ones of the Patio del Principe and the Alfonsí palace show formwork needles of 0.50 m and boards of 0.22 m Besides, they appear *calicastrados*. The different examples lack a differentiated foundation and plinth but some of them show lintel in the first formwork crates (photograph 3).

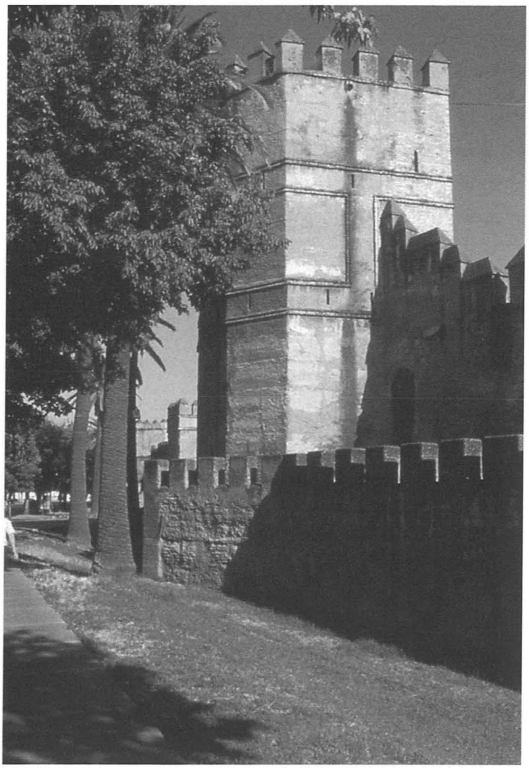


Figure 3
North-african wall of the 12th century (almoravid maybe). Third Precinct of the enlargement of the Alcázar, below the present mudejar palace of King D. Pedro

Chained tapia walls

The first chained tapia walls we find in Seville correspond to the second half of the 12th century, in the almohad period. In most of them the males are made of brick but there are examples of the first half of the 13th century made of stone. In any case, independently of the material of the males, they show two characteristics in common: thin lime joints and little intrusive chains, i.e. with little ledge (±15 cm.), so the consistency of the walls is based on the quality of the tapia wall.

There are two typologies in which the males are made of brick; these differ between them in the composition of the tapia, showing two constants as regards the males: 1.-use of the Arabic brick of one foot (28–14–4/5); 2.-Running and perpend bond. Only in one, late (from the second half of the 13th century) the chains are made of stone, isodomic in irregular bond and with different intrusion in the fabric to increase its cohesion as it happens in the Torre del Oro in Seville (1221). The typologies are the following:

Chained tapia fabric in gravel tapia brick and with high superposed formwork crates

This typology has appeared in different points of the Seville city wall. It appears in the east wall that nowadays separates the Alcázar and the Santa Cruz quarter (Precinct I) made of *zahorra* in the higher Muro de Agua (almohad period in the second half of the 12th century) with a tapia fabric identical to its contemporary one in the Macarena wall (Campos et alii, 1988), the Jardines del Valle (García-Tapia y Cabeza 1995) the Cabildo and Menéndez y Pelayo (Tabales 2002a) and in different parts of the enlargement to the south at the end of the 12th century as it has been shown by the drillings IV and V carried out in the stretch of the Galería del Grutesco (SE-IV, corner of the stretch close to the Cenador de Carlos V) and in the Torre de la Alcoba (SE-V). (Tabales 2001a)

This typology shows the following features: 1.-It is a chained tapia with common Arab brick males (24 × 14 × 4/5) in running and perpend bond with thin lime joints resulting in little intrusive chains in the tapia formwork crates. 2.-It is a gravel tapia made of lime, clay and medium gravel. 3.-the formwork crates are of long module (0.95 x 2.25 x 2 . . .) noting the impression of the wooden formwork needles of rectangular section every 0.50 m between the formwork crates, superposed directly one on top of the other. They appear well *calicastrado*. (Ramírez y Vargas 1995) (Figure 4).

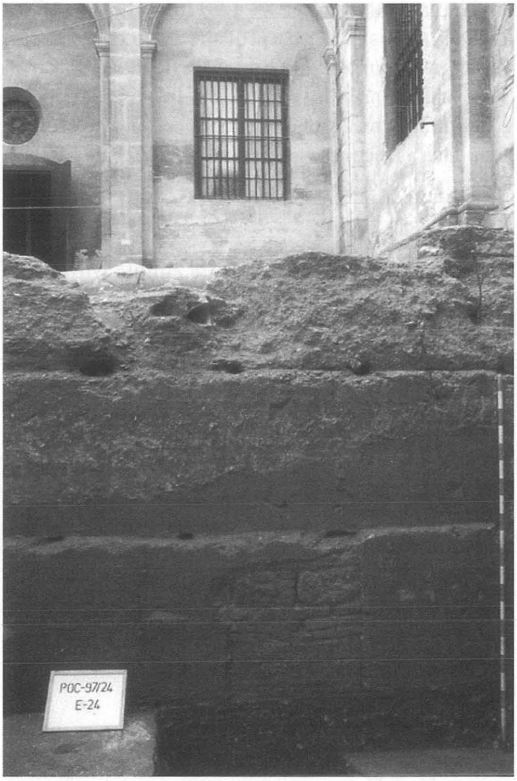


Figure 4
Walls of the Macarena. The fence is dated in the middle of the 12th century; the fore wall in 1212

Chained tapia fabric in rubble tapia brick and with high superposed formwork crates

It is a typology present in the almohad buildings from the second half of the 12th century and during the 13th century. It appears in the primitive entrance wall to the Palacio de la Montería (12th century, in the east

wall of the present Patio del León), in the recent walls of the Patio del Yeso (12th and 13th centuries) and in the walls of the Palacio de Crucero (12th and 13th centuries). The perimeter wall of the main mosque belongs to this typology too (1172–1174) (Figure 5).

It shows the following features, coinciding the first and third ones with the previous ones and the difference in the second one lies in the dominant aggregate.1.–It is a chained tapia with common Arab brick males (28 × 4 × 4/5) in running and perpend bond with thin lime joints resulting in little intrusive chains, i.e., they penetrate little in the tapia formwork crates. 2.–It is a ceramic fragments tapia made of lime, clay and ceramic fragments. 3.–The formwork crates are of long module (0.95 × 2.25 × 2 . . .) with formwork needles of 0.50 and they superposed directly one on top of the others. As in the previous typology, they are *calicastrados* and show a lintel in the second crate, lacking a differentiated foundation and plinth.

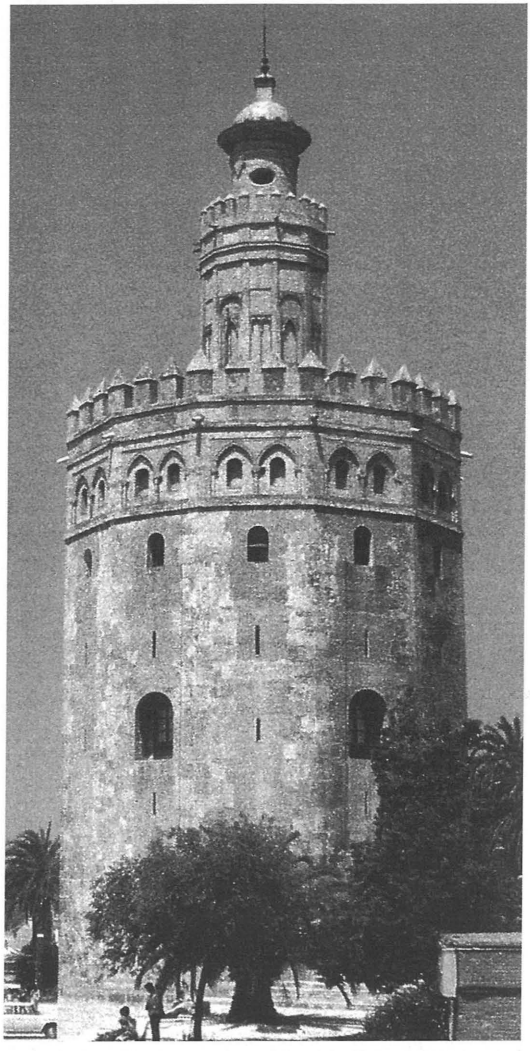


Figure 5
Almohad wall next to the *quibla* of the main mosque. It was raised in 1172

Chained tapia fabric in rubble tapia brick and with high formwork crates on brick courses

This typology is very similar to the previous one, showing the following features: 1.—It is a chained tapia with common Arab brick males (28 × 14 × 4/5) in running and perpend bond with thin lime joints, resulting in little intrusive chains, i.e., they penetrate little in the tapia formwork crates. 2.–It is a ceramic fragments tapia made of lime, clay and ceramic fragments. 3.–The formwork crates are of long module, 0.95 m The differences lie in two points: 1.–a stronger presence of the brick fabric compared to the previous one so that the formwork crates do not superpose directly one on top of the others but they are separated by one or two brick courses; 2.–The tapia formwork crates are less long (0.95 × 2 × 1.40).

This typology appears in the east fore wall and in the wall of El Agua (1212) and later, in the 14th century, it will last in the mudejar construction (Castilian), appearing, for example, in the mudejar churches of San Marcos and Santa Lucia around 1356. In these examples the tapia fabric appears with brick foundations and with one or several escarps and on brick plinths. (Tabales 2001b)

Chained tapia fabric in rubble tapia ashlar and with high superposed formwork crates

This typology appears in the almohad period in the first half of the 13th century. The most prototypical example is the Torre del Oro (1221) which shows

the following features: 1.–It is a chained tapia with isodomic stone ashlar males in running and perpend fabric with thin lime joints, resulting in little intrusive chains in the tapia formwork crates. 2.–It is a ceramic fragments tapia, made of lime, clay ceramic fragments and medium gravel and 3.- The formwork crates are of high module (0.95–2–25–2 . . .) with formwork needles of 0.50 and they are directly superposed. The example of the Alcázar appears calicastrado. (Tabales 2002b) (Figure 6).



Figure 6
Tower of Gold. Flanking tower of the fence of the Alcázar, dated in 1221.

Mixed tapia walls

So far we only have an example of what we call mixed tapia: to be more precise, the almohad walls of the Imperial street (12th and 1314th centuries) in which the formwork crates are inserted in a mixed fabric with alternating series of brick courses and rough stone. These ones are not directly superposed one on top of the other, but they are separated by the series of courses. By doing it so, the tapia loses importance on the resulting fabric. They correspond to a gravel tapia, made of lime, clay and gravel and the formwork crates are of high module (0.95 m.). It would be a mixed fabric of series of *gravel tapia courses in a high crate alternating with brick and rough stone series of courses* (2.3.1.) (Table 2).

The tapia wall in the mudejar Seville

Once reconquered the city of Seville, the first architecture built must have been done following foreign criteria, as least as far as big buildings are concerned. The gothic palaces of El Caracol in the Alcázar or in the Don Fadrique palace, both of the second half of the 13th century use brick and stone and they seem to elude tapia walls. Everything seems to indicate that in the rest of the city no new houses were built, at least at a large scale, due to the magnitude and splendour of the conquered Seville and the settling problems derived from the Castilian repopulation. However, from the 14th century on, thanks to the presence of a strong mudejar community and to the necessity of renovating the constructions and building new churches on top of the mosques, we appreciate an explosion in the use of tapia walls under formal parameters derived from the symbiosis between the latter almohad architecture and the vision of the gothic foundation. Among the examples found so far, there are two typologies.

Common tapia fabric of minute rubble with high superposed formwork crates. (2.1.2.)

In the place known as *Muro de la Judería*, partially conserved in the San Marcos and Jewish quarters, datable at the beginning of the 14th century, we find a tapia typology which is exceptional for this time but

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Table 2
Identification of the main types of Sevillian tapial wall. 12th century

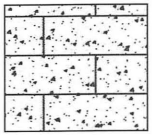
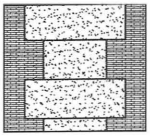
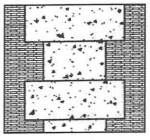
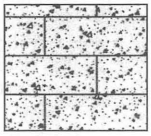
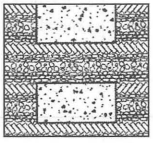
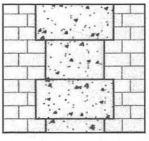
Cronology	Scheme	Module	Composition	Males	Formwork crates superposition	Foundations	Evidences
Almorávide/ Almohade First half of the 12th century		Formwork crate: 0'95×2'...×2'20 Formwork needles: 0'50 Boards: 0'22	Lime Sand Gravel Calicastrado	Lack of males	Direct superposition	Lintel in the second and third formwork crate. Lack of a differentiated foundation Lack of plinth	Wall below Patio del Príncipe and Palacio del Rey Pedro I.
Almohade Second half of the 12th century		Formwork crate: 0'95×2'25×2'.. Formwork needles: 0'50 Boards: --	Lime Clay Medium gravel Calicastrado	Brick of 28×14×4/5 Thin joint of lime. Running and perpend bond. Little intrusive chains	Direct superposition	Lintel in second formwork crate. Lack of a differentiated foundation. Lack of plinth.	North African wall of Macarena, Jardines of the Valle, Wall of the Higher Wall of the Agua, The Cabildo, Menéndez y Pelayo
Almohade Second half of the 12th century and first half of 13th		Formwork crate: 0'95×2'25×2'.. Formwork needles: 0'50 Boards:--	Lime Clay Ceramic fragments Calicastrado	Brick of 28×14×4/5 Joint thin de lime. Running and perpend bond. Little intrusive chains	Direct superposition	Lintel in second formwork crate. Lack of a differentiated foundation. Lack of plinth.	The perimeter wall of the Main Mosque 1172–1174. Primitive entrance wall to the palacio de la Montería. 12th century Recent walls of the Palacio del Yeso. 12th and 13th centuries Walls of the palacio del Crucero. 12th and 13th centuries

Table 2

Cronology	Scheme	Module	Composition	Males	Formwork crates superposition	Foundations	Evidences
Almohade Second half of the 12th century		Formwork crate: 0'95×2'..×0'50 Formwork needles: -- Boards: --	Lime Clay Gravel	Lack of males	Direct superposition	Lack of a differentiated foundation. Lack of plinth.	Wall in almohade palace of the Montería.
Almohade Second half of the 12th century		Formwork crate: 0'95 × ¿? Formwork needles: -- Boards: --	Lime Clay Gravel	Mixed fabric of brick and rubble series of courses alterning with tapial	Tapial alterning with brick series of courses	Lack of a differentiated foundation. Rubble plinth	Almohade Walls in Imperial Street.
Almohade First half of the 13th century		Formwork crate: 0'95×2'25×2'.. Formwork needles: 0'50 Boards: --	Lime Clay Medium gravel Ceramic fragments Calicastrado	Isodomic stone ashler Thin lime joints. Little intrusive chains	Direct superposition	—	Tower of the Patio del León. Torre del Oro. 1221

we begin with it because it is a common tapia. It is a controversial case, a strong battlemented wall with a width of 1.40 metres and made with superposed formwork crates without chains, of a military style to the latter almohad walls after 1172 although later (Figure 7).

Chained tapia fabric in rubble tapia brick and with high formwork crates on brick courses

We already saw this typology in the African period. To be more precise, it appeared in the east fore wall and in one of El Agua (1212). It presents the following features: 1.–It is a chained tapia, with progressive brick males very well bonded, made in common Arab brick (28 × 14 × 4/5) in running and perpend bond with thin lime joints resulting in little intrusive chains, i.e., they penetrate little in the tapia formwork crates. 2.–It is a ceramic fragments tapia, made of lime, clay and ceramic fragments. In general terms it will be of less quality than the almohad one (less proportion of lime and less time of tamping down in thicker layers) and 3.–The formwork crates are of long module, of 0.95 m., i.e., the crate maintains the almohad module but its number decreases inside the wall, which will usually have plinths and foundations with bigger lintels (Table 3).

This tapia wall is used in the Alcázar (in the Palacio del Rey Don Pedro and in the Salón de la Justicia), in the mudejar churches (San Marcos, Santa Lucía, El Carmen . . .) and in the domestic edification (many of the present dividing walls and façades

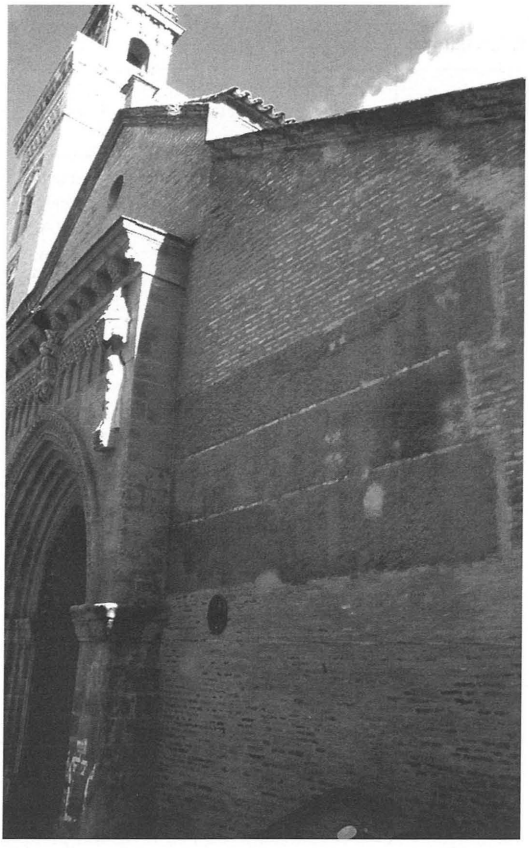


Figure 7
Wall of the Jewish quarter. Beginnings of the 14th century



Figure 8
Main door of the mudejar church of San Marcos. Middle of the 14th century



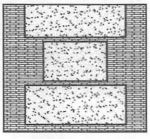
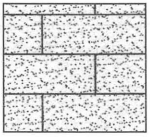
Figure 9
Windowed balcony of the Catholic Kings in the Palacio del Rey Pedro I, in the Real Alcázar. Last years of the 15th century

derive from this period and even from the almohad period) (Figures 8 and 9) (Table 3).

Tapia walls in the modern age

From the 16th century on, the presence of tapia formwork crates in the brick walls will be regular. The separation brick courses will increase from two to three from the 16th to the 18th century. The composition will lose in consistency, relegating the use of clay or gravel to the walls of buildings of special quality like part of the Hospital de Las Cinco Llagas, built by Hernán Ruiz in the middle of the 16th century. We distinguish two typologies although the difference between both of them only resides on the composition of the tapia wall, gravel (3.2.1.) or ceramic fragments (3.2.2.): in both cases the formwork crates have a measure equal or superior to 95 cm of height and the separation is of at least two brick courses, very intrusive chains (very pronounced) of bricks of 28 × 14 × 5/4, bonded roughly and with wide mortar joints poor in lime. The foundations of these fabrics are usually made of brick, in escarps and with high brick plinths. The surfaces are *calicastradas*. In fact, we

Table 3
Identification of the main types of Sevillian tapial wall. 13th to 15th centuries

Cronology	Scheme	Module	Composition	Males	Formwork crates superposition	Foundations	Evidences
Almohade 13 th century **Castillian** (mudéjar) 13th and 14th century		Formwork crate: 0'95×2'..×0'40 Formwork needles: -- Boards: --	Lime Sand Ceramic fragments	Brick of 28×14×4/5 Thin lime joints Little intrusive chains	One or two bricks courses	Brick foundations with one or several scarpes. Brick plinths	East ante fence and the wall of the Agua (Alcázar) 1212 Mudéjar churches (San Marcos, Santa Lucía) 1356
Castillian (mudéjar) 14th century		Formwork crate: 0'95×2'..×1'40 Formwork needles: 0'75 Boards: 0'16	Lime Sand Ceramic fragments Calicastrado	Lack of males	Direct superposition	Lack of a differentiated foundation Lack of plinth	Jewish quarters wall

could speak of a unitary typology. They are the following:

Chained tapia fabric in gravel tapia brick and of high formwork crates on brick courses

This is the type that we find in the Hospital de Las Cinco Llagas (1555–1560). In this case, the separation between the formwork crates is two brick courses

Chained tapia fabric in rubble tapia brick and of high formwork crates on brick courses

This is the predominant type and is the one that is present in most Sevillian convents and palaces of the 16th and 17th centuries (in Santa María de los Reyes at the end of the 16th century, in the Cuartel del Carmen in the first third of the 17th century, in Santa Mª de Jesús, . . .). The separation between the formwork crates varies from two to three courses and the brick plinths of the foundation of these fabrics are higher.

The tapia walls in the contemporary period

In the 18th and 19th centuries, a decadence in the technique is observed. We even see how samples of previous fabrics are destroyed and reused as building material. Besides, some fragments of the almohad wall are cut in blocks for their subsequent sale and are used to build houses attached to the fence. Some outstanding examples can be seen in the Navarros and Menéndez y Pelayo streets. We have plenty of examples of the use of this technique; in fact, our study has the 19th century as the chronological limit. (Tabales 2002a).

From this period we only find one typology, very similar to the previous one (high formwork crates, brick males with wide mortar joint*s and a very pronounced chai*n) but evidently degenerative from it and of a poorer quality as it can be appreciated in the Claustro de las Flores of the Hospital de Las Cinco Llagas in Seville. As a consequence, the number of courses separating the formwork crates increases and also their height (which do not appear *calicastrados*) and the material is of the lowest quality (sand and lime with rubble to which ashes have been

incorporated). As in the previous case, the foundations are made of brick, placing them on a high plinth of the same material.

Chained tapia fabric in rubble tapia brick and with high formwork crates on brick courses

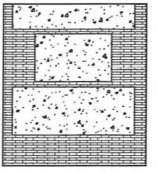
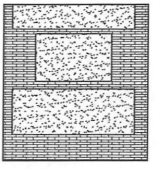
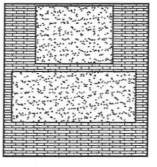
The formwork crates, whose height varies between 0.95 and 1.15 m., are separated by three brick courses which, due to the change of period, are now of less proportion (24 × 12 × 3) (Tabla 4).

Conclusions

From the exposed we can deduce some evidences that constitute a clear evolution in the Sevillian tapia walls. This evolution is mainly shown in the formal aspects of the fabric: metric, combination with other building materials, general composition, etc.

The differences are equally patent on the consistency level (the north-African wall of the 12th century is notably more resistant than the barbican of 1212)[1] and although physical and chemical studies[2] have been started in order to characterize the

Tabla 4
Identification of the main types of Sevillian tapial wall. 16th to 19th centuries

Cronology	Scheme	Module	Composition	Males	Formwork crates superposition	Foundations	Evidences
Modern Age 16th century		Formwork crate: sup. 0'95 Formwork needles: -- Boards: --	Lime Sand Gravel Calicastrado	Brick of 28×14×5/4 Wide mortar joints Very intrusive chains	Two brick courses	Brick foundations Scarps High brick plints	Hospital de las Cinco Llagas (Hernán Ruiz II) 1555–1560
Modern Age 16th and 17th centuries		Formwork crate: sup. 0'95 Formwork needles: -- Boards: --	Lime Sand Ceramic fragments Ash Calicastrado	Brick of 28×14×5/4 Wide mortar joints Very intrusive chains	Two or three brick courses	Brick foundations Scarps Higher brick plints	Convents, palaces, domestic buildings, churches . . . Cuartel del Carmen First third of the 17th century Santa María de los Reyes (end of the 16th century)
Contemporary Period 19th century		Formwork crate: sup. 0'95 (up to 1'15) Formwork needles – Boards: --	Lime Sand Ceramic fragments Ash	Brick of 24×12×3 Wide mortar joints Very Intrusive chains	Three brick courses	Brick foundations High brick plint	Claustro de las Flores del Hospital de las Cinco Llagas 19th century

components of the formwork crates, it is still very soon to formalize appreciations that, so far, are nothing more than reasonable suspicions related to a greater richness, care and depuration during the early almohad times (period of splendour of this technique)

In general terms, it can be appreciated a progressive increase in the height of the formwork crates from the 11th century (short measures) to the 18th centuries (highest measures), passing through a clear change in the metric since the north-African period (12th century).

The composition, either by the use of ceramic fragments or by *zahorra* or various materials, is indistinct according to the periods, but it must be noted a progressive loss of the fluvial aggregates since the 12th century (with notable exceptions in the public works of first order in the 16th century).

From the exclusive presence of tapia wall formwork crates (sometimes with stone plinths)in the 11th century, it will move on to the chaining with brick or stone during the 13th century and with the passing of the centuries the number of brick higher quality course (*verdugada*) separating the walls increases until it reaches its highest development in some baroque buildings in which the formwork crates alternate with the brick to fill in minor spaces.

In the future we will try to improve this first approach incorporating the analysis of other andalusi and north-African tapia walls; without any doubt, the local and regional variables, as Basilio Pavón mentioned in his treatise on Hispanic Muslim architecture, could lead us to wrong conclusions because of the lack of precision in the dating of most Spanish castles, palaces and buildings.

Luckily, in the last decade the number of archaeological excavations in the built heritage has increased so that we hope to establish some rules, maybe simple ones like the ones here exposed, once we have a sequence of types chronologically reliable

Notes

1. Works by the Gerencia de Urbanismo de Sevilla (Oscar Ramírez y J. M. Vargas 1995 and Tabales 1996) in several parts of the north African wall evidence a compression variable resistance near the 100 Kg./cm^2 (sometimes higher) while in ante fence it doesn't pass 40 Kg./cm^2.
2. Actually the Archaeological Research Project in Real Alcázar keeps studies about characterisation of medieval tapia walls with Antonio Ramírez de Arellano y Esther Enrique (Dept. Condensed Physics, University of Seville-CSIC, and M. A. Avilés y Pedro J. Sánchez, from ICM-USE)

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Historical earthen architecture and construction in the Mediterranean Region. What future for such an exceptional cultural legacy?

Hubert Guillaud
Alejandro Alva

The historical earthen architectural heritage represents a remarkable cultural significance in the whole of historical resources, as it shows an evident expression of the memory of the builders of humanity, since the most ancient times. Earthen architecture is present on all the continents. Moreover, the building cultures based on the use of raw earth (wattle and daub, adobe, pisé) are omnipresent in the history of Mediterranean civilisation.

Facing the challenge of the conservation and «mise en valeur» of the Mediterranean earthen architectural heritage, we can certainly propose drafting orientations and strategies for the future that would push on the development of integrated activities in the following correlated fields: education (for teaching a discipline), research (for elaborating a specific science), application and situated projects (for developing a professional practice), advocacy (for raising an institutional and public awareness), knowledge basis (for structuring a discipline), and a data base (for more information accessibility). This approach is proposed by the «Project TERRA»[1] jointly developed by CRATerre-EAG, ICCROM and the Getty Conservation Institute.

The proposed communication should briefly present the importance of the historical earthen architectural heritage in the Mediterranean region, its general state of conservation and the paths for developing a cultural management which are proposed in the «TERRA-Med Project».

Historical Earthen architecture in the Mediterranean Region

The primitive periods

The regions of the Mediterranean Levant and of the Taurus-Zagros Arch the unbaked brick was the vector of a fantastic urban development during the IVth and IIIrd millennium B.C. despite this building culture has been emerging since the VIIIth millennium as the famous site of Jericho has testified. At that time, the habitat is settled on hill slopes, both embedded in the thickness of the soil and partially aerial. It is basically oval and round shaped. The walls are erected with a kind of small hand-shaped earthen «breads» which seem to have been built at their plastic state, without any mortar. This technology has been also observed on the site of Mureybet, Syria, where the common people's houses of the VIIth Millenium B. C. are round-shaped, partially embedded in the slopes of the tell, exhibiting small indoor spaces typically organised around a central space. Apart from archaeological sites which are exhibiting remains of entrance gates covered with arches and barrel or inclined vaults built in unbaked bricks, the excavations carried out in the territories of Near Orient have given few examples of the use of vaults or cupolas for the common roofing of vernacular people's houses of ancient times. Some clues of the possible design of these people's houses, during the Assyrian Times, have been given by graffitis which

have been observed on the site of Niniveh. It seems that the conical-shaped vault, or corbelled cupola, might have been used. We could compare the morphology of this design to the shaping of some vernacular houses in actual Syrian villages of the region of Aleppo which are today much more rare but testifying of this legacy tracing back to ancient times.

In Thessaly, Greece, primitive human settlements of the Mediterranean Europe are dated from the mid-VIIth millennium (around 6500 B.C.), tracing back to the protoneolithic phase, so before the apparition of the ceramic. This primitive habitat settled on the border of the Aegean Sea, in the deep layers of Sesklo, show huts presenting variable layouts, lightly buried in the soil. They are constructions made of wooden poles probably supporting walls in wattle and daub («*torchis*»). The VIth millennium confirms the inputs of the Anatolian and levantine building cultures up to Thessaly, Crete and Cyprus. At the apogee of Sesklo, during the mid-Vth millennium (5500–4400 B.C.), the dwellings of the upper levels are both built in wattle and daub and unbaked bricks. They look much more structured and they adopt the rectangular layout. These houses should have been two slopes roofed and some of them should have been two-storied. Earthen walls are insulated from the humidity by stone basements, as the stone is also used for the defending walls and for some outdoor terraces of the site. However, these houses are still settled as independent farms and they are not really showing a social villager organisation. But, at that time, the basic layout of the habitat is evolving to the «megaron» typology which will predominate in the Ancient Greek architecture: one main room with a hearth slightly embedded in the soil, preceded by an open hall without frontage except a portico supported by one or two massive poles. The same type of habitat has been found at Dimini (South of Sesklo) and will predominate during the Recent Neolithic Ages (4400–3000 B.C.), even if there is an evidence of a hierarchical society which is testified by the existence of some more important dwellings, settled on top of the hills of Sesklo and Dimini.

The Aegean World and the continental Greece

In the Aegean world, the Ancient Bronze Ages (3000–2000 B.C.) which corresponds to the first civilisation of the Cyclades all over the islands, is marked by the development of the construction adopting the apsidal megaron type of layout, mainly built in stone and protected by thick defending walls including oval shaped towers (acropolis of Kalandriani, at Syros, sites of Paros and Melos). On Crete, during the Ancient Minoan (2700 B.C.), at Vasikili, the «house on the hill», with its irregularly designed rooms, seems to announce the future palatial complexes. The earth might have been used, according the «cob» technology, piled up in casings at its plastic state. The larger use of the unbaked brick seems to have colonised the Peloponnese just before the IInd millennium. In the deep layers of Lerne III, the «house with tiles» is erected within a fortified perimeter in the centre of which the American excavators have found this large building (25 × 12 m) showing a row of 4 rooms (among three of them present corridors). The starting of a stair confirms the existence of a second floor. All the thick wall of this house is erected in unbaked bricks and put up on a stone basement. These walls are plastered with stucco.

During the Middle Bronze Age (2000–1500 B.C.), a very clear fracture can be observed between the continental Greece, which is submitted to Indo-European invasions and a cultural regression, and the Cyclades which seem to face a sudden rise of civilisation. In fact, in the Peloponnese, the Mycenaenan fortifications are increasing. These fortified positions (Mycenae, Tyrinth, and Pylos) are protecting a rural habitat of shepherds, which is settled all around them. This habitat is not well known but seems to have been very precarious and maybe built in both wattle and daub (for inside partitions), and unbaked bricks (for main walling). The «house of the wine merchant», and the «house of the oil merchant», so called by the excavators, describe the characteristic megaron in three parts, inherited from the Thessalian Neolithic, with the *«prothyron»,* or portico with two columns *in antes*, the *«prodomos»,* or small anteroom, and the *«domos»,* or larger room organised around the hearth. But there is no many remains of such habitat, except some smaller villages that are conserving their fortifications built up in unbaked bricks.[2] After the brightening up inputs of the IInd millennium, some have spoken of a «coming back to the degree zero of the architecture». At the same time, the insular context of the Crete is favouring the harmonious development of the Minoan Civilisation. The superb

«lighting palaces» of Knossos, Phaistos and Mallia, invested by the environmental nature, are offering a very refined decoration. An omnipresent light comes in the rooms and cheers up the building materials: the tuff, the gypsum, the schist and the marble which are used for the main walls, the unbaked brick for the partitions or the wood used for the carpentry, the columns and their capitals, the porticos, the door and window frameworks.

On the Greek peninsula, at the Mid-Xth century, in Eubia, the city of Lefkandi seems to have played an important part since the IInd millennium. It has come to light an important structure of monumental character. This is a *Herôon,* an edifice that is consecrated to the cult of a Hero, which might foreshadow the first Greek temples. This apsidal-shaped building of 45 m long, the original walls of which are partially conserved at a height of 1,50 m for some parts, exhibits an unbaked bricks walling put up on a stone basement. The earth was used as bonding mortar. The inside facings were plastered with gypsum. The roof was supported by an axial bearing system of wooden columns in line erected on stone slabs and the pavement was in clay. This elaborated earthen architecture corresponds to a time that someone have called «the second starting of the Greek architecture». In fact the political context of that times (IXth and VIIIth centuries), testifying of a reorganisation in regional states gifted with a relative stability, is favourable to such architectural fulfilment. At Smyrna, architectural restitutions which have been proposed by R.V. Nichols, are showing a typology of habitat, also apsidal-shaped and protected by a thick fortification in unbaked bricks and stony material which is built up behind a cyclopean stone facing. The unbaked bricks are quite big (51 × 30 × 13 cm). Within this protected area of more or less 35000 m^2, oval houses of about 3 × 5 m are settled without any specific order and also built with unbaked bricks of the same size, but not put up on a stone basement nor footings. Their outdoor facings are plastered. During the VIIIth century, the apsidal megaron will evolve to the rectangular shaping and Hellenic settlements will extend up to Sicilia and South Italy (see Incoronato, near Metaponto). The walling building system in unbaked bricks, put up on a basement made of stone or big pebbles bonded with clay mortar, is widely used in the new Italic settlements (Sibari, Amendolara, Heraklea, Velia, Morgantina, Himere) and up to the Iberian peninsula as are testifying the Valencian sites of Vinnaragell and Pena Negra. It is undoubtedly from these coastline sites that the unbaked brick will penetrate up to Catalonia and then to Aragon. At the same time, the Greek architecture is starting a petrifying process, particularly for its religious architecture and the unbaked brick will be more reserved for the megaron-type housing. The Greek domestic architecture will develop later and stayed small, obscure and uncomfortable for a long time. This is only with the coming of Democracy (508–507 B.C., at Athens), that the civil and domestic architecture will present more elaborated principles as like the *«stoa»* (open portico with columns), the Hypostyle room, as the organisation of the rooms around an indoor peristyle. But during the blooming period of Pericles (453–429 B.C.), at the feet of the brightening up Acropolis of Phidias, the popular city is lying down in dense housing neighbourhoods mainly built in unbaked bricks or in post and beam structures filed up with such materials which are thatch-roofed and Athens is looking like a great township. For the best living conditions, these houses are plastered with stucco or painted in bright colours.[3]

Phoenicians and Carthaginians

When the Phoenician, pushed away by Assyrian attacks, will have to transfer its civilisation to the littoral of North Africa, it will call for this technology of the compacted earth in wooden casings, associating it to the unbaked brick, for building the new Punic settlements. The birth of Carthage is taking place around 814–813 B.C. The original settlement that was originally a modest colony called *Qart Hadasht* (*Karchedôn* for the Greek and *Karthago* for the Roman), or «new town», will become a powerful Mediterranean capital with an exceptional destiny. At is *acme*, by the IInd century B.C., its population should have reached about 700 000 inhabitants. During its first stage of development the original township was settled on the slopes of the Hill of Byrsa, configuring a modest acropolis. At its blooming stage, the city was covering about 2000 hectares, including several commercial and military harbours. This Great Carhage laying down in a perimeter of 32 kilometres was protected against threats that should come from the back inside land with an advanced line of fortifications. A twin rampart encircled the city itself.

The French campaigns of excavations carried out on the Hill of Byrsa, by 1974–76, directed by Serge Lancel,[4] are clearly showing that Carthaginians have firstly use the slopes in order to establish a necropolis, the tombs of which being dated from the VIIIth up to the VIth centuries. Then, this necropolis has been embanked to settle a neighbourhood of metalworkers with their forges and workshops. It is only by the beginning of the IInd century that this site has welcomed planned people's housing units, the famous «Hannibal's neighbourhood» and its housing blocks A, C and E which can be visited today. These housing units exhibit a standard layout organising the rooms around a small indoor yard that is accessible by an entrance corridor. As confined spaces for the starting of staircases (probably in wood) are visible, these units might have been two or three-storied high. They have been settled according an orthogonal urban design which looks typically Hellenistic. Today, looking at the houses walling remains of the famous Blocks B and C, along Street II, one can clearly see the eclecticism of the Punic building culture were, the use of the blocking stone masonry cohabits with unbaked brick and *«pisé»* masonry, burn brick elements. This is the typical *«opus mixtum»* or *«opus africanum»* (masonry within structural pillars in stone or burnt bricks) which has been related by the Roman. Only the main façades on the street were built with stones, put up in great bonding. These stones were coming from the Cap Bon, extracted in the quarries of El-Haouaria. After the total destruction of Carthage, the Hill of Byrsa has been totally embanked by the Roman. This huge work was carried out to redesign and level the hill in order to settle the post Roman edifices, including the new Basilica and Forum. For that purpose, to warrant the stability of the new development ground and fond the edifices, the Roman have erected in compacted earth numerous thick footing columns some of them reaching a height of 9 m. These impressive footings in *«pisé»* are still visible.

Italy and southern Gaul

The site of Rome was already occupied during the Bronze Age as the findings of the *Forum Boarium*, dated from 1500–1400 B.C., are testifying. Later, at the beginning of the Iron Age (VIIIth century B.C.), several of the famous seven hills were inhabited as are confirming two Villanovian hamlets which have been excavated on the Palatine. These hamlets seem to have been unified around a kind of common civic centre settled on the actual Forum area. At that time, the habitat is still very primitive. It gathers huts or wooden shanties, rectangular or oval shaped, supported by a central wooden pole and perimetric smaller poles. It is slightly embedded in the soil. The roof might have been in thatch and walls in wattle and daub. In that way, Rome, at the beginning of the VIth century is just an agricultural township when it is influenced by Hellenic inputs which were previously introduced by Greek colonists settling in Campania by 750 B.C., and then transmitted by the Etruscan domination. By that time Central Italy knows a real metamorphosis. The wooden huts, plastered with earth and thatch-roofed of the primitive Rome, are gradually giving place to rectangular houses built in unbaked bricks. Similarly to the first Etrurian temples, the first sacred and public monuments of the Republic (IVth and IIIrd centuries) should have been erected with unbaked bricks and tile roofings gradually replace the thatched roofs. An orthogonal town planning takes the place of the previous modest and disordered settlement. Great rectangular housing blocks, sometimes fortified by an embankment of earth, the *«agger»,* preceded by a large ditch, are erected (see Marzabotto, near Bologna). By the Vth century, Rome extends its domination from the Latium all over the Italian peninsula. New colonies are settled on the base of the fortified camps of the military legions, adopting a regular town planning *(Decumanus and Cardo).* At this epoch of great change, the unbaked brick that was previously the main building material is much more used for the construction of modest people's housing, for indoor partitions and most of the time for filled up post and beam structures. This popular technique of wood and earth construction will be used up to the epoch of Nero (37–68 A.C.) and a lot of housing units have been destroyed during the dramatic fire of the year 64. The same building process has been commonly employed for the construction of numerous new settlements of the Roman colonists when the Empire will extend in actual Europe, particularly in Gaul. So many remains of such building practices have been found on French Gallo-Roman sites, in Lyon, Vienne or Vaison-la-Romaine, in Nîmes, Lattes or Arles. The recent works of the French archaeology carried out on

the Mediterranean regions are confirming a large use on the unbaked brick, but also of the *«pisé»* during these epochs (IIIth to IInd centuries B.C.).[5] On the Celto-Gallic territories, the Iron Age develops a habitat settled in *oppida* gathering small wattle and daub or cob houses. In southern Gaul, on actual territories of Provence, from Languedoc to Roussillon, Hellenic influences are introduced with the creation of the first Greek trading settlements, as *Phocea* (Marseille), *Antipolis* (Antibes), *Agathe* (Agde), *Nikaia* (Nice), and also on the Iberian territories with *Emporion* (Ampurias). This takes place between the VIth and the Vth centuries B.C. By that time, the «civilisation of *oppida*» of the southern Gaul[6] will rapidly adopt the Hellenic inputs and particularly the use of the unbaked brick which will substitute for the wattle and daub construction all over the indigenous settlements of the Gulf of Lion coastline. The evidence of such a change in the building practices is visible on sites as Ruscino, Enserune, La Lagaste or Entremont. Simultaneously, there is a gap between the coastline and inland settlements where the wattle and daub and cob building technology are still predominating. Then a slipping between the earth and stone construction will gradually extend in numerous *oppida* during the IVth and IIIrd centuries.[7]

When Caesar will begin the conquest of Gaul (59–51 B.C.), he observes a local construction where the use of rudimentary building materials is very common. The *«vici»* (rural townships) and the *«aedificia»* that he describes in his *«De Bello Gallico»* might have been undoubtedly built in wattle and daub or cob, evenly in unbaked bricks. In his *«De Bello Civili»,* Cesar gives an other description of the *«murus gallicus»* which is made of earth, stone and wood. At the end of the Ist century, and up to the imperial Ages (in 31 B.C., after the victory of Actium), Rome is in its major part built in unbaked bricks or in post and beam structures filled up with this material. In his «Roman History» (XXXIX, 61), Dion Cassius evokes a rising of the river Tiber that over flooded all low neighbourhoods of Rome and notes that «the houses made of bricks took water from everywhere and collapsed». Nevertheless, the *«lidio», «crudi lateres»* or *«latericus paries»* still remained the building material for the popular housing, beyond the Augustean Ages. As previously observed, Vitruvius[8] was taking the unbaked brick into great consideration, recognising «its greatest utility so long as it does not load the walls too much». He willingly calls for its use «so long as someone building with it should take the necessary care for putting it up correctly». He precises that to build with several floors, the unbaked brick construction should be twin layers bonded *(«paries biplinthius»)* or even three layers bonded *(«paries triplinthius»).* However, after this dramatic flooding of the river Tiber, the use of the unbaked brick was pushed away from the city as soon as building rules were promulgated which prohibited the construction of thick walls, obliging to respect a maximum thickness of one foot and a half (44,3 cm) for all party walls. By that time, for erecting high buildings, the Roman civil builders prefer to use post and beam structures filled up with a blocking masonry of mixed rubble stones and fragments of tiles, reinforced by stone bond beams. By the same time, in his *«Res Rusticae»* (I, 14,4), Varron evokes the *«pisé»* construction as regards as rural fencing walls *(«maceria»)* protecting an agricultural farm located on the Sabine territory. He describes the technique as *«a mixing of earth and gravel which is agglomerated in casings».* He also observes the common use of the unbaked brick *(«lateribus crudis»)* for the construction of such rural fencing walls.

With the coming of the Julio-Claudian Dynasty (Tiberius, Caligula, Claudius and Nero), the tuff, baked bricks and blocking stone rubble-masonry with bonded cut stones or bunt bricks facings, are becoming the main Roman public construction techniques. By 120 A.C., in his *«Augustus»,* evoking the Emperor Augustus, Suetone writes that he has embellished Rome and preserved it from the flooding and firing danger. He writes that Augustus praised himself to have received a town made of unbaked bricks and having left it in marble *(«marmoream se relinquere, quam latericiam accepisset»).* But the popular urban and the rural architecture, as the construction in numerous far-west provinces of the Roman Empire, are going on using the unbaked bricks. In Gaul, the *«pax romana»* will favour an urbanisation pressure around the *«vici»* and other rural townships as well as the construction of numerous *«villae».* As Strabon is observing in his *«Geographia»* (IV, 4,3, and XII, 1, 67), *«Gallics are building large round houses with wooden planks and wattle walling that they are covering with thick thatched roofs».* So,

Tacitus in *«Germania»* (XVI, 3), on the subject of the German housing was noting that *«they do not make use of stones nor tiles; for every building purpose they use raw materials («materia informi») without taking care to any beauty or attractiveness; some parts are more carefully plastered with a so pure and so brightening earth that it imitates the painting and colouring strikes.* Numerous settling sites of the Gallo-Romans *«villae»,* as far as over the actual northern territories of France, in Picardy, that have been identified by the famous aerial archaeology works carried out by Roger Agache and Bruno Bréart,[9] are confirming the existence of basements put up in blocking stone rubble-masonry *(«caementicius paries»)* that should have been heightened with earthen building materials, unbaked bricks, or wood and earth walling whose falling in debris are clearly visible thanks to the colouring variety of the soils showing darken spots attesting of the ancient presence of buildings. The more elaborated *«villae»* have often made a distinction between the use of the earthen building technique, mainly reserved for the *«pars agraria»* (agricultural outbuildings), and stone or burnt brickwork technique for the residential building or *«pars urbana».*

In North African countries, or «Maghreb»

In Tunisia, from the beginning of the Ist century to the IIIrd century A.C., the unbaked brick or *«pisé»* construction was very common in the Province of Byzacena as are testifying excavated dwellings in Acholla, the famous *«House with red columns», «Asinius Rufinus» House» or «Neptune's House»,* which are dated from the reign of Marc-Aurele, or by 170–180 A.C. In «Neptune's House», the *«pisé»* is used for buttressing the pressure of a cistern located in the *«viridarium».* In Uzitta, near Souss, several houses have been excavated showing a common use of earthen structures put up on top of stone basements. It might have been the same in the near Province of Tripolitania. The city of Thysdrus has passed on among the best-conserved testimonies of the public and domestic architecture of those times. In the *«Lucius Verus' House»* and in the *«House with frescos»,* a great number of unbaked brick (50 × 35 × 9 cm) walling, put up on of stone basements built according the *«opus Africanum»* type have been observed. These remains of earthen walls are plastered with a 2 cm thick lime mortar. Again in Thysdrus, the *«House of the death masks»,* which is of Punic type, is built in *«pisé»* with 50 cm thick walls erected on top of a 70 cm high basement made of blocking stony masonry. During the period of Roman occupancy, in Tingitania (Morocco), the construction in earth has been attested on the site of Volubilis, particularly in the *«House with the cistern»* located nearby the North of the triumphal arch. This large dwelling, dated from the IInd century A.C. was covering a private bath of about 150 m^2 that has been dated from the Ist century where «all walls are presenting a stone basement at a variable height, when the elevation was in *«pisé»* or unbaked bricks»[10]. The southern neighbourhood of Volubilis, called in other words the «craftsmen's neighbourhood», or «indigenous neighbourhood», has revealed numerous findings of fit in together houses, gathered in a very dense cluster, all built in unbaked bricks laid on with a clayey mortar on top of 80 cm high basements in stone blocking. The size of the common bricks is 44 × 28 × 8 cm.

The common ancient earthen building cultures legacy in the Mediterranean region

Beyond the Fall of the Roman Empire, the earthern buildings practices will quasi definitively mark the rural and a great part of the urban people's housing construction, particularly over the Mediterranean regions, up to the modern times. This cultural legacy has resisted to the coming back to the dark times of the High Middle Ages (from the Vth to the Xth centuries) that have known a regression to more common and simple building practices. In Italy, where various rural traditions can be still observed; that one of the *«casoni»,* in the *«Friouli»,* or that of the *«pinciaie»* of Abruzzi. But also the *«ladriri»* or *«mattoni»* of the Sardinian *«Campidani»* (from Cagliari to Oristano) which could be certainly connected to the ancient Carthaginian influences. Equally for the Iberian Peninsula. In Spain, region of Catalonia (around Barcelona), where people was still building in «adobe» and in «pisé» *(«tapia»),* only just twenty years ago. Also in *«Tierra de Campos»* (Castilla and Leon, north of Valladolid and Palencia), where a very nice tradition of pigeon towers can be still observed. In Portugal with the similar building culture of *«taipa»,* in the region of Algarve where, closely to the border of Spain, can be still observed

the legacy of the typical *«Al Andalus»* earthen building process which is inherited from the period of occupancy of the Moors: the thick walling built up in *«tapial»* are faced with a raw stonework masonry put up with a lime mortar. In France, the vernacular earthen architectures are a typical feature of the rural landscape in almost all regions of the country. The northern territories are typically concerned by the tradition of the construction in posts and beams *(«colombage»)* filled up with wattle and daub or «*torchis*» as we can observe in Champagne, around the city of Reims. In the south, the Mediterranean legacy of Ancient Greece and Rome, the Carthaginian inputs and more recently the Arabic influences, are particularly evident: «adobe» (unbaked brick) all over the southern territories, from Aquitania to Provence, *«pisé»,* all along the Rhone and Saone River valleys up to the Forez (Auvergne, Central Massif), and in Dauphiné (North of Isere).

What future for such an exceptional cultural legacy?

Just a glance at the mobilisations in Mediterranean countries

All over the occidental Mediterranean countries, the earthen architecture rebirthing movement is in progress. After having welcomed the 7th International Conference on the Conservation and Restoration of Earthen Architecture, «Terra 93», in Silves, Algarve, the *«Dirección Geral de Edificios y Monumentos Nacionais»* (DGEMN, Ministry of Housing) of Portugal has created the *«Escola Nacional de Artes e Oficios Tradicionais»,* institutionalising a *«Programa Pedagogico, Curso de Construçâo Civil Tradicional Construçâo de Terra».* In this school that is training future craftsbuilders and contractors, located in Serpa (Southeast of the country), young people can learn the adobe and *«taipa» («pisé»)* building techniques to use them for the restoration of the national earthen architectural heritage, or for developing a contemporary architecture. Spain begins to worried about the conservation, maintenance and revival of its so nice *«tapial»* heritage located in *«Tierra de Campos»* now exposed to great threats of destruction because of an endemic exodus of the local population to big towns, pushed away by the searching of employment and better living conditions. Italy has organised conferences on this subject in order to promote a national network of specialists. This country counts now on 9 studying groups with university settings, which are dedicated to the research and education covering the field of earthen architecture.[11] In Sardinia, an important programme for the conservation of the traditional architecture of the *«Campidani»,* built in *«ladriri»* («adobe»), has been launched some 10 years ago, which is supported by the regional authorities. In France several regional groups gathering professionals (architects, building contractors, scientists), now attempting to federate their efforts in a national network called «Ecobâtir» (Ecological construction), are developing studies and projects aiming at promoting the conservation of our national earthen architectural heritage and the new construction in earth. Recently, a «Global Contract for Development», supported by the main regional and local territorial communities of the Rhone-Alps Region (Southeast of France), has included in its economical and cultural objectives of development an action entitled «valorisation of the *pisé».* This programme that concerns 46 communes of North Isere has been launched last year and will run up to the year 2005. This movement for a revival of the earthen architectures that took place in the previous quoted countries is now enlarging its impacts and inputs to many other parts of Europe. So were recently created in England (Devon) the *«Out of Earth»* movement, and in Germany (in the *«Die Grünen»* motion), the *«Lehmbau»* network, which are already both very active. Who will stay more out of concern of such an international Renaissance of the Earthen Architecture?

A project proposal for the future of earthen architectures in the Mediterranean region

Summarised projects Background

During the year 1987, the *«5th International experts meeting on the Conservation of Earthen Architecture»*[12] that has been held in Rome, jointly organised by ICCROM and CRATerre, was finally recommended to push on the development of a specific set of institutional activities in this field. These activities should mainly focus on a specialised education and should support the setting up of specialised teaching

programmes in academic institutions. The educational dimension of this project was justified by an evident statement shared by several international organisations: the dramatic lack of professional competencies that should be necessary for conserving a world-wide earthen architectural heritage (archaeological sites and historical buildings) threatened of destruction. In 1989, following this recommendation, a specific project is inaugurated, jointly defined by CRATerre and ICCROM, the *«Project Gaia»,* adopting as main objectives: i) the development of professional training courses; ii) scientific investigations; iii) co-operation projects and, iv) the dissemination of the knowledge. From this time, four international courses on «The Preservation of the Earthen Architectural Heritage» («PAT» Courses) will be successively organised in the School of Architecture of Grenoble (France), in 1989, 1990, 1992 and 1994. Supported by a reflection on the didactics, the pedagogy and the teaching methodologies, this initiative is growing and leads in 1994 to the creation of the *«Project TERRA»* that enlarges the initial partnership of ICCCROM and CRATerre to the Getty Conservation Institute (GCI, Los Angeles, USA). Considering the importance of the strengthening of specialised regional centres, this remodelled project has already realised two *«Pan-American Courses on the Conservation and the Management of Earthen Archaeological and Historical Earthen Architecture»* that have taken place in Peru, in 1996 and 1999. These two courses have given an impulse to the exchanges of experiences among a larger international network of professionals (historians, archaeologists, architectural conservators, architects, cultural site managers) that has been initiated since 1989 with the previous «PAT» Courses organised in France. Since that time, this international network has had several opportunities to be gathered, thanks to successive international conferences that have been hold in USA («Adobe'90», in Las Cruces), in Portugal («Terra'93», in Silves) and in England («Terra 2000», in Torquay). Simultaneously, over the past few years, the *«Project TERRA»,* has given its support to the organisation of several other national conferences or events: in England, Italy, Germany, Czech Republic, favouring the creation of several ICOMOS «Sub-Committees on the Study and Conservation of the Earthen Architecture». The *«Project TERRA»* has also launched and supported several scientific research activities. Among them can be raised up the publication of a first specialised bibliography covering the field, a «Research Index», a «Literature Review», a preliminary reflection aiming at «structuring the discipline of the earthen architecture conservation», and more recently, a fundamental scientific research on the cohesion and the loss of cohesion of the earth material.[13]

The «TERRA-MED» Project

Summarised presentation

The «TERRA-MED» Project aims at applying the operational strategy that has been already tested since 1989 by the «Project Gaia», and then by the «Project TERRA», to the Mediterranean Region. The project is carried out in concordance with the targeted objectives and fields of the EUROMED HERITAGE Programme (for its second phase).

The main objective of the «Project TERRA» is to develop the conservation and the «mise en valeur» of the earthen architectural heritage, through a network of institutional co-operation, leading to activities in the fields of education, research, projects and awareness. All these activities will be supported by a knowledge basis and a data bank.

The large scale of the «TERRA-MED» Project covers all countries of the Mediterranean space testifying of an important earthen architectural heritage and being part of the European Union or associated to the Declaration of Barcelona: Portugal, Spain, France, Italy, Greece, Turkey, Cyprus, Syria, Lebanon, Israel, Palestinian Authority, Jordan, Egypt, Tunisia, Algeria, Morocco.

Conclusion

Preserve the techno-diversity: an essential option for tomorrow

For warranting this so-called «sustainable development» —or maybe «post-development»—, the new paradigm of the IIIrd millennium founded on a global alliance aiming at protecting the biodiversity, haven't we the obligation to preserve and pass on the cultural memory which is conveying intangible sense and values that are so indispensable to every

living society? Is not there any alternative for conserving our architectural heritages expressing shared universal values? On such a point of view, the earthen architectures —existing over all continents— should not be essential to this protection and passing on of our inherited cultural, bio and techno-diversity? Might not they offer an alternative to this homogenising building and architectural transculturation that could be devastating? In this way, it should be upon the indissociable triptych «conservation —sustainable development— modernity» that could raise a «vision» for a recreated future of the earthen architectures useful for the coming out of more viable societies generating new specific as diverse equilibriums between «men», their environments and their cultures.

The erosion of the techno-diversity comes under a cultural amnesia, the consequences of which could be dramatic for the worldwide socio-economical system. The preservation and the revival of this techno-diversity are becoming a factor of vitality for the future of the planet. But, considering the challenge for

Project objectives

TERRA-MED Project

CONSERVATION AND MISE EN VALEUR OF THE EARTHEN ARCHITECTURAL HERITAGE IN THE MEDITERRANEAN SPACE

Objective:
A recognized heritage

CO-OPERATION

Objective:
A regional Mediterranean network

EDUCATION	**RESEARCH**	**APPLICATION**	**AWARENESS**
Objective: A taught discipline	Objective: A specific science	Objective: A professional practice	Objective: A social endeavour

KNOWLEDGE BASIS

Objective:
A structured field

DATA BANK

Objective:
An accessible knowledge

the coming out of a sustainable development, we have to produce a huge effort for taking stoke of our techno-diversity, for a better knowledge and more understanding of this «building intelligence» and go on updating, enriching our cultural legacy by a more appropriate use of the potential of our technologies. But, there is another danger: to be frozen in an «illusion of the permanence», that is also an untenable «reactionary» attitude. Based on such considerations, the conservation of the earthen architectural heritages, the sustainable development of a scientific research and specialised education in this field, today, are undoubtedly a decisive contribution for tomorrow; this is part of a shared effort —to be developed at the world scale— aiming at reconcile Man and History, and with its cultural diversity that we have now to consider as a paramount option and vector for a «local» development to be balanced with a «global» development. This is a possibility for opening new paths to a «post-development» which could not be only based on the omnipotence of money (profit) and macro-techniques which are generating much more cultural, social and material impoverishment, too much more unacceptable human poverty.

Notes

1. The Project TERRA on the Study and Conservation of Earthen Architectures has been inaugurated in Novembre 1997, following a previous project called the *«Gaia Project»* which was created in 1984 by CRATerre-EAG and ICCROM.
2. According a description written by May Veber, *«Mycènes, creuset tumultueux de l'Hellade»,* 1980.
3. According the historian, geopgrapher and philosopher Dicearque (347–285 BC), quoted by Lewis Mumford in his *«La Cité à travers l'Histoire»,* ed. le Seuil, Paris, 1964.
4. Lancel, Serge, *«Byrsa I» and «Byrsa II»,* Mission archéologique française à Carthage, rapports préliminaires des fouilles (1974–1976 and 1977–1978), vol. 41, ed. De Boccard, Rome and Paris, 1979 and 1982, respectively, 381 p and 382 ill., 417 p. and 613 ill.
5. See Desbat, Armand, *«La région de Lyon et de Vienne»,* (The region of Lyon and Vienne), in DAF (Documentation of the French Archaeology) n° 2, *«Architectures de terre et de bois»* (Earth and wood architecture), 1985.
6. 277 units of *oppida* have been identified in the Var, more then 300 in the Alps of High Provence and more than 200 in the Gard, all actual territories of southern France.
7. Fiches, Jean-Luc, *«Habitat et fortifications, la civilisation des oppida»* (Habitat and fortifications, the civilisation of oppida), in Archaeologia n° 35, June 1979, pp. 67–75.
8. Vitruvius, *«De Architectura»,* Livre I, 3, 8, and Livre II,3, translation by Claude Perrault, ed. J. B. Coignard, Paris, 1674.
9. Agache, Roger and Bréart, Bruno, *«La terre crue dans les constructions traditionnelles»* (The unbaked earth in traditional constructions), in dossiers histoire et archéologie n° 79, Dec. 1983, Jan. 1984 (pp. 16–23).
10. Slim, Hedi, *«La Tunisie»*, in DAF n° 2, op.cit., note 29, pp. 35–45.
11. These groups are set in the universities of Torino, Milano, Genova, Udine, Venecia, Firenze, Macerata, Pescara and Cagliari
12. This meeting was following previous scientific events covering the topic: in November 1972, Yazd, Iran, *«First International Conference on the Conservation of Monuments built in Unbaked bricks»;* in March 1976, still in Yazd, *«Second International Symposium on the Conservation of Monuments built in Unbaked bricks»;* in October 1977, Santa Fe, USA, *«Working Session on the Adobe Preservation»;* in September-October 1980, Ankara, Turkey, *«Third International Symposium on the Earthen brick (adobe) Preservation».*
13. See: *«projet Gaia project», «Bibliography on the Preservation Restoration and Rehabilitation of Earthen Architecture»,* ed. CRATerre-EAG-ICCROM, Rome, Italy, 1993, 136 p. (900 documentary references). The *«Research Index»* has been published by the *«Project TERRA».* Based on a wide survey carried out close to architectural conservation professionals, it precises the main scientific research directions for the next years, according the professionals' needs and expectations. The *«Literature Review»,* prepared and draftly written by CRATerre-EAG (Arch. H. Guillaud), and then revised by a corpus of North American and European scientists covering various fields of research, will be published by the GCI late 2002. The research on the cohesion and loss of cohesion of the earth material is driven by CRATerre-EAG (Eng. Hugo Houben), in partnership with GCI and ICCROM Research Units and several other Research laboratories and Units of French universities-UMR-CNRS.
14. This communication is integrating contributions of other researchers of CRATerre-EAG, particularly for the last part dealing with the presentation of the «TERRA-MED Project». We particularly raise up here, as main contributors: Eng. Hugo HOUBEN and Arch. Eng. Marina TRAPPENIERS.

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Constructive experimentalism and innovation technique in the 18th century French treatises. The *discovery* of Félix François d'Espie

Riccardo Gulli

> Monsignor, a construtive treatise about a new type of roof, it may appear not worthy to be offered at yuor attention. Perhaps I could be blamed for the initiative in submitting it at your attention, but your acceptance will justify my act. I hope you will approve it since I trust my discovery to be useful: great men appreciate objects for their utility and not for their magnificent.

In this manner, with a dedication to the Duke of Bellisle, begins the treatise *The way to render any type of buildings fireproof or adjusted for the construction of tiles and plaster vaults, commonly defined flat vaults; and about brick roof, without wood, called tile roofs* pubblisched in Paris by Félix Francoise d'Espie in 1754.

These first introducing words, clearly state the author's concern to give to print a strictly applicative contents work. A superior reason research, which could justify the interest for the description of a technical procedure, is as a matter of fact easely understandable if related with the specific theoretical futures which identifies the treatises concerning the building vaults construction during the XVII century and in the first part of the XVIII century in France.

The birth of new disciplinary branches, as for example the sterotomia, means in this sense the direct and tangible evidence of a progressive specialization process oriented towards an always stronger separation among the different knowledge and competences which belong to the area of project design and architectural construction.

Starting from the forties of the XVII century and through the studies of M. Jousse (1642), of G. Desargues (1640), F. Derand (1643) up to A. F. Frézier (1737–1739) about a century later, the interest on the vault building, it appears to be almost exclusively oriented towards setting up of suitable instruments for scientific description able to give an exact geometrical description.

Through the project of the *Encyclopedia*, the boarders of knowledge in architecture and construction are ridiscussed and repositioned: a new sensitivity oriented towards the complexity arising from the variety of knowledge takes place instead of the research of indubitable truth and therefore a tendency to a requalification of trade.

To this respect d'Espie's treatise, represents a specific and relevant editorial phase, which unable to determine a focal point on the terms of this transition.

The attention given to the study of a construction system, as a consequence of an unlearned knowledge of the skilled workers, finds its own way of legitimation to obtain the approval by the Istitutional figures, the Academies, in charge to evaluate the scientific validity requirements.

The innovative value arising from technique, considered as a *discovery*, together with its instrumental and utilitarian target, symbolizes for d'Espie the categories and conceptual instruments through which it appears to be possible to give new relevance and dignity to a study regarding construction.

In the introducing section it is written:

Many people are reluctant and sometime they are right, to accept new discoveries. However, I hope that when they will have evaluated with care this proposal of mine, they will understand the advantages and the importance . . . I refer to a new type of roof which I executed for a house in Toulouse three years ago. This roof is made exclusively with bricks, plaster and lime; neither wood nor iron are used. This is the reason why I called it bricken roof. It is sustained by flat vaults, which represents an admirable and singular technique which many people do not approve only for the fact of not knowing it, and which has a very antique use in the Roussillon, and more recently in Languedoc and in other neighbouring provinces. The Duke of Belleisle has given to this country the first example of this type of vaults. He has used some carpenters from Perpignan, the most expert for this type of work, to build such vaults in his castle in Bizy (d'Espie 1754, 7–9).

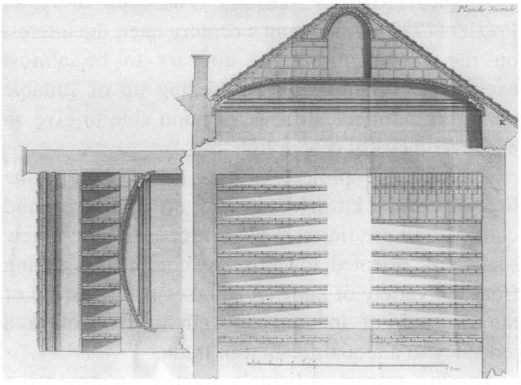


Figure 1
Roussillon vault example. (d'Espie 1754). Planche seconde

Therefore, a very ancient practice but at the same time, very innovative. The potential contradiction which apperently raises from such an association actually means an important indication which refers to a different way of cosidering the notion of «progress», intended as upgrading of knowledge in the relationship created with the values of Tradition and History.

The *discovery* about which d'Espie refers to us is not describable in terms of «scientific innovation», or better in terms of a progressive exceeding of the last obtained result, of the last invention.

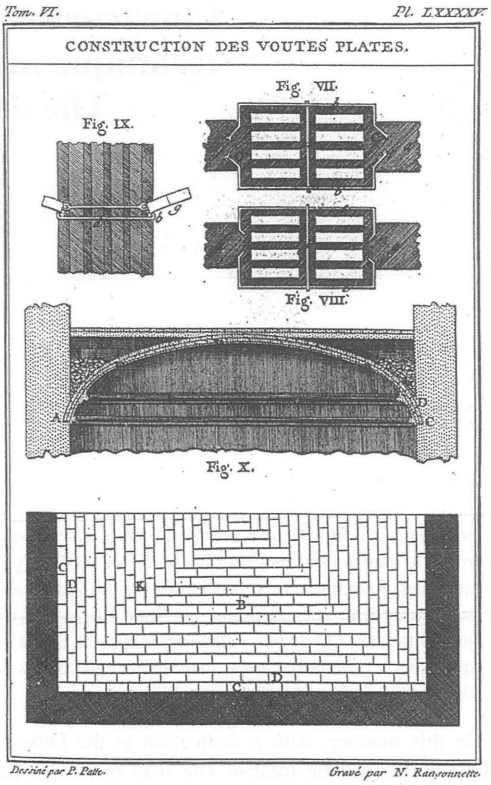


Figure 2
Drawing of imperial vault of Toulouse house by P. Patte. (Blondel 1777). Panche 95

In parallel with this attitude, which however remains and informs the scientific cultural background of that period, a new approach to knowledge comes up which looks with a renewed interest and on a different point of view to the historical experience, in its different articulations from the theoretical ones to the applicative ones, restitutes as feedback.

The d'Espie's notion of *discovery* should therefore be considered as belonging more to the category of *recognition* than to the one of invention.

To this extent is possible to find common aspects with the contemporary research promoted by the encyclopedists in the attempt to make a complete rewriting of knowledge and in this way rearising even what it remains hidden, for its specific nature, in the dark folds of the practice.

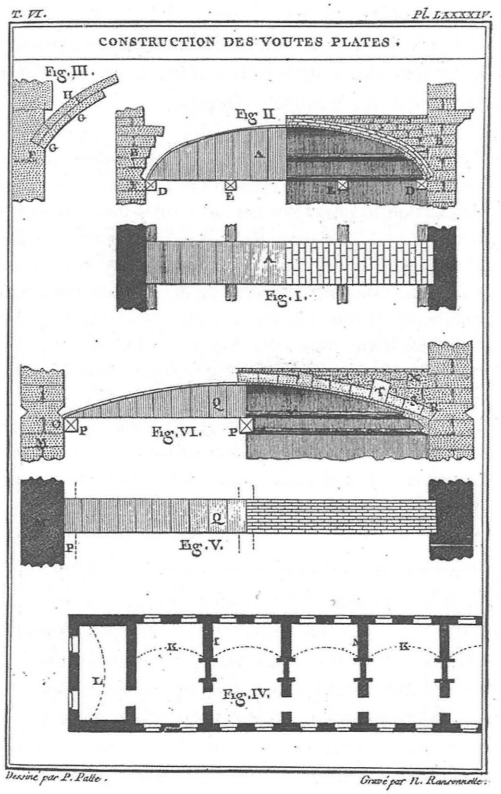


Figure 3
Drawing of Bizy Castle vault (Figs. 1, 2, 3) and of Versailles War, Marine and Foreign Offices (Figs. 4, 5, 6) by P. Patte. (Blondel 1777). Panche 94

In the same time, the critical status of the doctrinal separation between *idea* and *technique*, between *theoretical speculation* and *application moment*, opens up to a new process of experimental knowledge which finds out again in the «utilitarian» and «functional» concept of the technique one further way of scientific-cultural legittimation passing through the acknowledgement of the *usefulness* both as a social factor and as a real contribute to reach a common good.

The utilitarian point of viev assumes, an important rule inside the illuministic culture, in determing and in the same way in justifing the objectives identified by the new knowledge strategies in the variety of disciplinary fields, acquiring time by time different and multiple descriptions.

In the project design and architectural construction section the *funcionality* concept is often linkes with the one of *rationality*, branching off on two parallel paths: on one side the research moves on the field of natural phenomena understanding through elaborating scientific theories and models of explanation, the first steps on the way of a future devolopment of Construction Science; on the other side, as already mentioned, it is enhanced the trial to gather *reason and work*, *science and technique* through revaluating the minor arts and a reapproching between *conceiving* and *practice*.

D'Espie treatise condensade and exemplifies both orientations showing in the same time the contrattidions of a new and different knowledge approach. The theory supported by d'Espie is focused on the performance requirements offered by this type of construction, both in terms of structural behaviour and in order to the house funcionality.

Let us stop on the first matter. The arguments developed on the statical working principles applied on the vaults executed with this technique, called *flat vaults* or *imperial vaults*, is set up starting from the exact understanding description of the constructive nature of this type of vaults through a detailed exposition of the technical process and of the needed rules for a correct execution.

In one section of the treatise it is said:

> The bricks used in Perpignan to build these vaults, and which have been used by myself, mesure 10 fingers, 5 width and 1 thickness . . . Other centring have not be prepared since they are not needed to form the imperial or any other geometry which will be given to the vaults: they are quite light and can be built with discarded wood from our construction: therefore a minimum cost is forseen. These centrings are not made to support the vault, but only to give a guideline to the carpenter. These vaults can be executed on old walls, provided that they are solid enough, and also on new walls, provided that they are let consolidate for six months before building up the vaults, so that a natural settling is granted. This is an essential caution which I myself found very useful. To guarantee that these vaults will be solid enough and will not cause any thrust on the walls, it has to be made during the constuction process a recess (niche) of 3–4 fingers along the room's perimeter, in the point where the vault has to be built, in a way that the first brick can be set on the side and almost vertically on this recess (making and angle of about 80°) . . . These vaults may be simple or double; the first type are used when the upper floor should be

> inhabited, or in those cases they do not have to sustain other loading apart from their own. The double vaults result to be in anycase more stable; this is obtained laying down a second layer of bricks covering the first one and paying attention that the joints of this brick layer never match with the first one (d'Espie 1754, 19–25).

The process described by d'Espie strictly reproposes such a practice whose presence and diffusion cannot actually be constrained only to the French regions of Languedoc and Roussilion, but to the whole territory consisting of Catalogna and the other northern regions of Spain. The most directly and truthful evidence of the belonging of this technique, called *tabicada*, to the ancient constructive spanish tradition, it will be offered by Fray Lorenzo de San Nicolás treatise (1633), which comprehends a detailed decription of the rules that consents an exactly *bovedas tabicadas's* construction, or on the other hand of tile vaults that presents two or more layers (Gulli and Mochi 1995).

But independently from the questions about cultural and geographic paternity of the technique, which appears meaningful regards the important rule shows by the comprehension of the exactly constructive procediment at the ratio of the corrispondence with the stuctural working hypothesis about this kind of vaults.

D'Espie says:

> People could say of the existence, in others places, of collapsed flat vaults; centerly I will agree with them and answer that these one were construed by bad masons which hadn't respected the exactly construction rules, or that had used shoddy materials. But, otherwise they couldn't present any example of flat vaults that had upset walls. I know the some are collapsed because they will be too much flat, but these, with the collapsed, didn't origined orizzontal forces against walls (d'Espie 1754, 56).

This is therefore the fondamental passage of d'Espie thesis which consents to recognize the pecularity and in consequence the innovative value, that marks these constructions. Vaults carried out by this technique and belonging to this typology don't generate orizzontal forces to the supports. A such assertion, reconsidered through light of knowledge and theorical hyphotesis about the static of arches formulated by scientific culture of that time, from De la Hire (1666; 1712) to Belidor (1729) and Couplet (1731–1732), appears indeed extremely surprising. The comparision with traditional brick or stone vaults is discussed in a treatise's chapter:

> Traditional brick or stone vaults in voussoir manner with lime mortar, required particolary attentions and the application of principles and art's rules that couldn't be neglected . . . Monsignor Belidor, in the treatise dedicated at ingegneer's science, did demostade by geometrical way these principles. It might be desiderable that who is interessed on construction building knows that very well and that do not make the mistake to follow a fallacius procedure based on a practice which foundations will be everytime fallacius if not confirmity by theory's laws . . . Instead for flat vaults, belonging to another nature, is not necessary that during construction same rules and principles of traditional vaults are followed (d'Espie, 1754, 40–44).

The art of building, with its rules and its own principles, is therefore subject to the verified by *theory*. But the recognition of the pre-eminence assigned to the scientific dimostration in convalidating figures coming out from experience opens up to formulate new ones just it is declared the discordance existing between *theory* and *practice*, between conceptual models and phisical phenomena. In other terms, the theoretical hypothesis concerning the fact that the flat vaults do not push, while being avaluated by the scientific truth to be recognized as worthy, striectly required the identification of scientific instruments and methods able to describe it. The lack of a general theory which would at that time unable to explain the static function of the vaults operating out of the field of the studies based on the «wedge» model, obliged therefore d'Espie to go through the experimental evalutation way. D'Espie says:

> There are finally the proofs which I have done myself and which will not give minor confirmation of their solidity. I had made built an imperial vault in carriage, in a squared room with more than 4 and half tese for side; but even before having it completed, I made it load with 1.750 bricks layed on the extradoss, each of them weighting 25 pounds, which was corresponding to 4.375 pouns load that I left on the vault for two days, making the carpenters from Perpignan which built it treable . . . I made then discarge it with the result that not withstanding the enormous load and right often the lightness, no alteration

> occured . . . In conseguence of this experiment, what could reply whom declared that flat vaults aren't solid, that generate horizontal forces against walls and that occurred a great thickness of these ones to be sustained? All examples I has already referred would make them thinking about their prejudices (d'Espie, 1754, 52–56).

The polemic vein that coulors d'Espie words to declare the truthfulness of experimental's procediment as a thesis's confirmity, reproduces the terms of famous ideologic's quarrel which accompanies, in the first part of century, the wellknown of the San Pietro's dome riability by Giovanni Poleni e Luigi Vanvitelli. Poleni himself will state in a passage of the *Memories* that his knowledge analysis «does not accept the sublime and abstactes calculations and that it wants real proofs for itself: to these therefore in the intend to better discover the truth, we must go through. These notions have to be clared up with the experiments to be able not to use abstracted doctrins which could in this way denieted» (Ramazzotti 1984, 28).

The attempt promoted by the illuministic research to reduce the space will separate the forms of an ideal language, the matematical analysis and the Rational Mechanic, from the phisical reality of constructions, finds as a matter of fact in the laboratory research an important mean able to provide a scientific description of the phisical phenomena through the experimental figures interpretation. Such an orientation is well translated in the Académie Royale des Sciences acts, in which are preserved the results of numberless experiments carried out by the experts of that time, as for example those onesmade by H. L. Du Hamel about the wood mechanical properties, which as feedback and under a different historical prospective, contains common elements of interests with d'Espie studies. The conclusions to which Du Hamel come to with reference to the behaviour of a wooden beam laying on the medium point and loaded at the extreme, concerns the importance asumed by the cohesion force of the wooden fibres guarantee a high value of resistance «such as that wooden beam costitued by very strongwood fibres, that are not stricked one to the other, it might break under the weight which another beam but with weaker and closer fibres would sustain» (Du Hamel 1742, 340).

Du Hamel intuition, which he is not able to translate in scientific terms, it is the support given by the side adherence between one fibre to the other or in other words the existence of tangential tensions which raise up in case the bending stress is followed by schear. It is only after the development of Charles Coulomb (Coulomb 1776), which the first mathematical formulation in terms of adherence and cohesion concepts was obteined with the following use in the statical theory of arch stone. From the theoretical stand point the qualitative evaluation of the phenomena described by Du Hamel, appears however important since it represents the first contribution to the further studies concerning the elastical futures of the materials and on the applicative methods which will come in use in the nineteen century. At the same time, d'Espie percives that the structural behaviour of the bricken layer vaults differs from the hypothesis of the «wedge model» and this comes out from the different costituent relationschip which results from the material depending on the peculiar constructive organitation which marks out this type of vaults.

In the following d'Espie statement that these kind of vaults «do not originate thrusts like the other vaults, and this can be as the plaster, when is well linked with the single brick, determines the vaults to be a sole body which do not have any specific role playing with the single parts: they will never push each other, since their assembly make them as a solid mass which will self contain without ever splitting, even if lighly supported» (d'Espie 1754, 57), it is in fact contained an important observation which anticipates, even if only from qualitative point of view, the following difference made between the structures describable through the theory of the stiff body and those to which the mechanic of continuos is applicable.

The intuition of d'Espie will find as a matter of fact confirmation only later on, with the experimental study carried out by Raphael Guastavino (Guastavino 1893), in the last decades of 19th century and with the hypothesys on the elastical characteristics of the materials and therefore on the capacity of the bricken layer vaults to sustain the tensile tensions induced by the shearing and bending stress, elaborated by some spanish experts in the first part of the 20th century (Bayò 1910).

But the experimental texts which d'Espie gave to support his own theory were not sufficient to obtain the official approval by Académie Royale de Architecture.

On august the 19th 1754, Michel Toannevot introduced the treatise to the Academy members for their judgement; in the last of the five sessions dedicated to the matter evaluation, on april the 28th 1755, the council, unanimously gave its evaluation (Lemmonnier 1915, 6: 222–225, 228, 234).

The system approval was constrained to the observance of primary condition: instead of tiles, ordinary bricks 2 3 6 3 12 inches should have been used and layed down on edge as obtain resistent section of 6 inches. In a few words a bricken vault layed down as for the traditional system.

The inability shown by the Istitution to understand and consequently to give legitimation to a rule which did not correspond to the canons and precepts fixed by the construction habit, is indicative of the difficulty expressed by the scientific community of that time to promote innovative methods and systems buildings techniques.

As very clearly observed by Luigi Ramazzotti,

> while moving inside a not scientific techniques world, to evaluate them with a systematical and severe approach, the Illuminsm goes through the way of the precise knowledge of the traditional building procedures and of the expertise trasmitted in the building techniques. Viceversa in the operational side there are any records in terms of innovative building techniques. In this field the real impact of Ecletism can be evalueted better on the methodological side then in terms of innovation (Ramazzotti 1984, 30).

In such a way, if on one side d'Espie system will acquire a relevant editorial fame, appearing as a costant reference also in the following manuals and treaties in the end of 18th century and at the biginning of the 19th century, on the operational side the applicative examples of this technique will be constrained inside single and isolated experiences, without carryng on a relevant change in the building attitudes of that time.

The reasons of the disparity between the considerable editorial diffusion of this technique towards d'Espie treatise —with english (London, 1756), german (Frankfurt and Leipzig, 1760) and spanish (Madrid, 1776) versions— and the failure on the side of constructive practise, belongs to the complexity that characterize every historic event, not describable through deterministic interpretations. Therefore, only a few hypothesis will be explained.

First issue, about which it exists a wide agreement in historical analysis, concerns the self-referring which can be found in the 19th treatises, as for the continuous elaboration and re-writing of information previously pubblished.

The case of Toulouse tile roof, was variously described by M. A. Laugier (1755, 2° ed.), by D. G. Shebers (1761), by Joaquín de Sotomayor (1776) as a critic version of d'Espie treatise, by P. Patte (Blondel 1777), by J. B. Rondelet (1802), by J. N. L. Durand (1802–1805), by Pasley (1826), by U. Vitry (1827).

Therefore, considering the following editions and translations pubblished in the course of 19th century, is possible to notice that the Toulouse experience will be alive and wellknown for about one hundred years.

In the other hand, in the field of constructive practice, the employment of this technique, out of the original context, was conditioned by the *pre-scientific* world that characterize the d'Espie experimental approach and the entire illuministic experience.

The failure of the experiment leaded inside the War School of Paris (Bauchal 1887, 238; Blomfield 1921, 2: 126–127), at the presence of the First Royal architect, A. J. Gabriel, will be recorded and annotated by Patte (Blondel 1777, 6: 116). The employment of Paris's plaster, which offered a different behaviour in terms of resistance and shrinkage compared with which was in use in Toulouse, summed to the unskilfulness of skilled workers on leading the constructive process, were be, according to author, the main causes of the unforeseen vault's collapse, as soon as constructed. To these reasons, for Patte, «this kind of construction have had a modest success in Paris».

The uncertainty showed by Royal Architecture Academy commission on attesting the scientific validity of the d'Espie constructive system, reinforced by the failure of War School experiment, will be assumed as two significant moments that had conditioned the employment of this technique in the building practice of that time, bordered inside the «cultured» dimension of the editorial project but devoid as an effective presence in the habit of erecting yard.

Only one building, from whose related in Blondel's treatise, that represents an application of d'Espie solution for the house of Toulouse, is Palais Bourbon, where, in occasion of the riability in 1764 for Prince Condè account, as new proprietary, was foreseen the

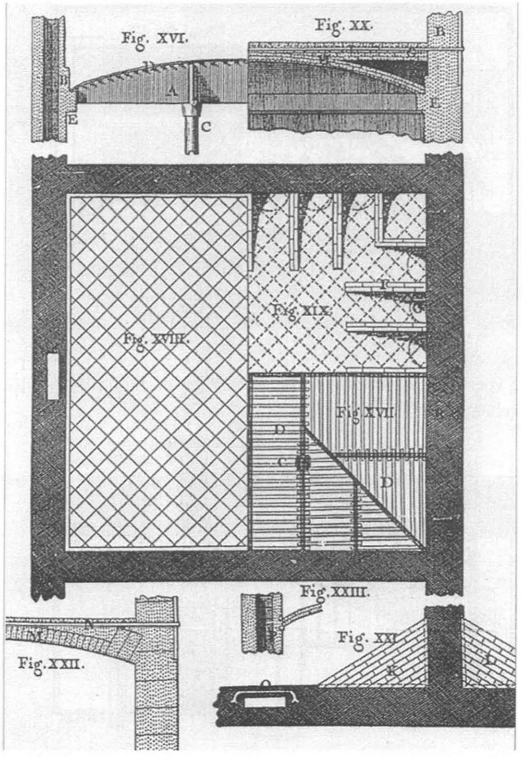


Figure 4
Drawing of Palais Bourbon's vault by P. Patte. (Blondel 1777). Panche 97

employment of flat vaults for middle floors and of a barrel vault for roof.

Omitting the case of the roof, not belonging to the category of flat vaults and for this substantially different, instead of particolary interest is the case of the vault described in Figure 4.

The vault, on square base and with profile section generated from a circle and not from ellipse, shows some particolarities compared with the one of Toulouse. The first regards the employment of *briques sillonnées*, or tiles with drills on the plane faces in according to have best proprieties in terms of strong adherence between plaster and brick.

A clearly clue of the consciousness of the importance assumed by «cohesion» force, as well as defined by Du Hamel, on conferring the capacity on resistance to shearing stress of multi-layers structures.

Besides, on extrados, there are tie-beams with bolts; a significant warning, in spite of d'Espie thesis, of the presence of thrusts along the vault's imposts.

In this case too, before the beginning of the construction, was requested to execute a prototype for a text, in the sight of a Royal Architecture Academy commission (Croÿ 1906–1907, 2: 320). The good result of the text, executed checking the vault's resistance under a load uniformly distributed, allowed the continuation of the brickwork, but at the same time, declared the mistrust in d'Espie theoria about the missing of thrusts: in fact, the response marked that the good outcome was in conseguence of the employment of tie-beams; an opinion originated from the observation of a vertical displacement, about two inches, suffered by one of the four walls as soon as constructed.

In the light of today's knowledge on structural analysis, the d'Espie thesis about the lack of thrusts, appears, under a strict theorical point of view, incorrect; or better, is possible to assert that the multi-

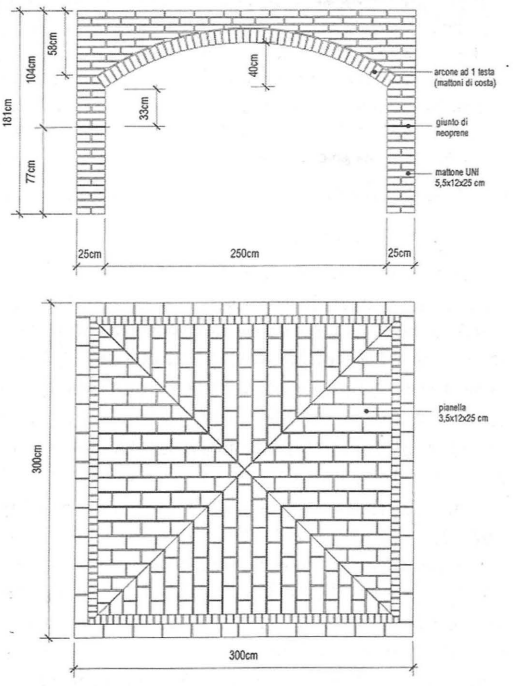


Figure 5
Experimental prototype. Plan and prospect

layers vault's structures are more rigid compared with traditional vaults of similar thickness, but this is not sufficient to consider any presence of actions along the vault's imposts.

This issue is widely confirmed by a sequence of experimentations leaded on constructive prototypes executed in laboratory (Gulli and Mochi 1995); in particolar, the good response in terms of little deformation for original mono-layer tiles scheet vaults afterwards reinforced by two more layer on the extrados, was been in evidence in the experimentation regarding a cross-vault of 3,00 m side and in the ratio of one to eight between rise and span.

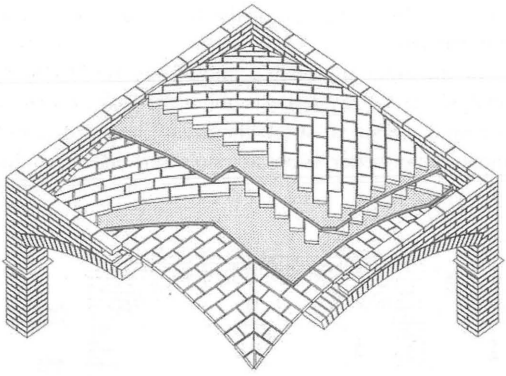


Figure 6
Experimental prototype. Axonometric of multi-layers vault

The main objectives of this experimentation were to put in evidence the way to employ the *tabicado system* as a restoration technique for mono-layer tiles scheet vaults; in addition to this aim, there was the exigence to realize the constructive procedures, in the passage between theorical explanation of a constructive rule and its translation in operative manner.

For example, d'Espie's hint on how do not tighten the vault against the perimetrical structure, in order to allow the horizontal shiftings following from the strains generated by loads, has been an important constructive device to garantee a correct working of vault's structure.



Figure 7
Experimental prototype. Construction of mono-layer tiles scheet vault



Figure 8
Experimental prototype. Laying of first layer's tiles on arch's extrados. On the left, is present the void space in order to allow the horizontal shiftings following from the strains generated by loads



Figure 9
Experimental prototype. Construction of mono-layer tiles scheet vault

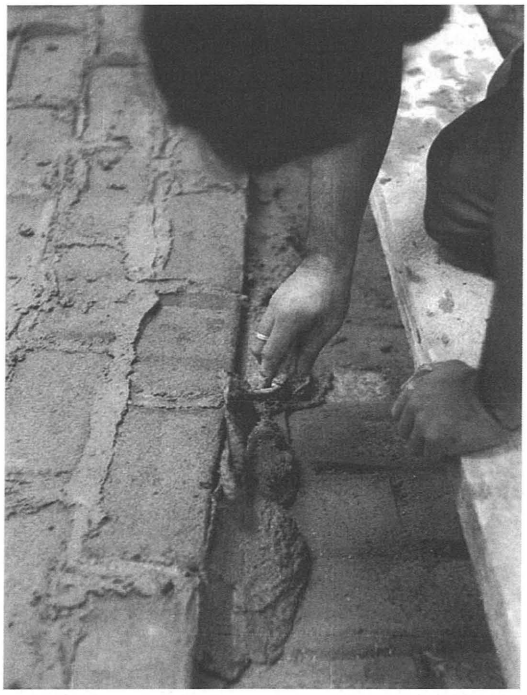


Figure 10
Experimental prototype. Construction of double-layer tiles

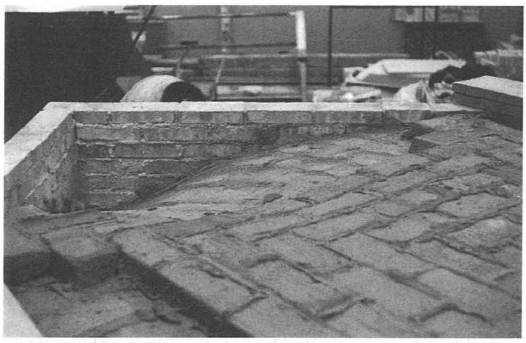


Figure 11
Experimental prototype. Construction of double-layer tiles

In the matter of structural working, the analysis of the tension stress under load, attest a remarkable increse in terms of stiffness of multi-layers vault compared with the original one (Fig. 12). An increase, however not sufficient to eliminate the thrusts. At the end of ripening, was gradually released the hooping tie-beams disposed along the line of the imposts. Progressively and inexorably, the vault's prototype collapsed following the typical kinematical situation with the rotation of the four supports (Fig. 13).

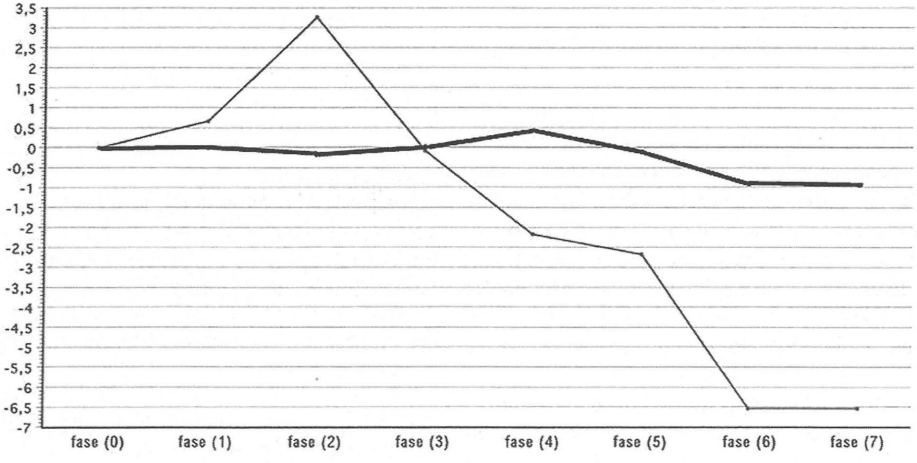


Figure 12
Graphic in which is represented a synthesis of experimental results. Relative values of vault's vertical translations (ordinate) relationed to the phases of loading (abscissa). The blank line indicated the condition of multi-layer vault, while the other, the state of original mono-layer tiles scheet vault. It is clear the remarkable increase in terms of stiffness of multi-layers vault compared with the original one

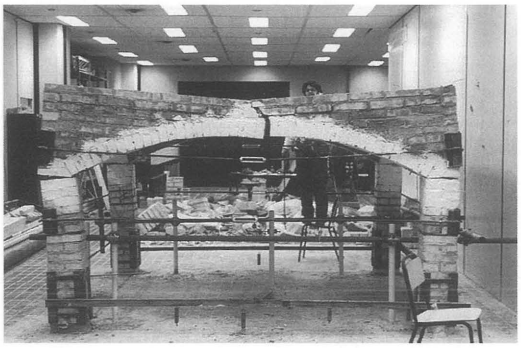


Figure 13
Experimental prototype. Phase of loosening of the hooping tie-beams

The experimental way followed by d'Espie, as the subsequency Guastavino's one, represents, for that time as today, an essential instrument to approach the comprehension of the peculiar structural working of this constructive system.

In fact, the refined numerical models for strcutural's analysis today in use, show margin of doubt, when the factors connetted to the sensibility of artisan's action and the presence of different materials combined in heterogenetic manner, play an important roll.

In conseguence, it is easy to comprehend the explanation given by Patte in order to the premature collapse of War School's vault, belonging to the use of Paris's plaster.

Under the hidden folds of a kind of learning that swings between the theorical speculation and the empiric data of experience, between *theory* and *practice*, rise and consolidate, rules, principles, technical procedures that declared themselves valid in the *act of construction*; at this dimension belongs the entire experience of *tabicado system,* of which, the d'Espie vicissitude, represents only a partial contribute.

As Patte said «the construction of tile's roofs has not reached the auspicate point of perfection and will be considered a very useful discovery if will be found a new system of doing it, that is light, solid and lasting at the same time» (Blondel, 6: 159).

An auspice and a forewarning, of what will be about a century later, when, on the hands of the Catalan Modernistic Movement' Magisters, will flower the extraordinary architecture vault's examples, characterized by a diversity and surprising employment of multi-layers vault's system.

Also in this case, not as an expression of logic originated from mathematic comprehension of fisic phenomena, at that time still uncertain, but as an epilogue of a kind of knowledge, that rises slowly inside the empiric data of experience.

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Theorizing the roof. «New» roof constructions in German countries at the end of the 18th century

Isabel Haupt

In the 16th century the Frenchman Philibert de l'Orme invented a new method of roof construction in which planks were nailed or pegged together in a semicircular form. This method never vanished totally in France. However, the starting-signal for a new fashion was marked by the erection of the dome of the Halle au blé in Paris in 1783 by Jacques-Guillaume Legrand and Jacques Molino, who used de l'Orme's method.[1] Its rise and decline can be pursued in an exemplary manner in Germany, where research over the last twenty years gives an excellent overview of the architects involved, expert discourses and the fabrication methods.[2] In the following I will concentrate on Prussia and Saxony and discuss one example in greater depth. This allows an insight into the transfer of new technological knowledge, in this case from France via Prussia —the most important German region associated with this construction method— to its southern neighbour Saxony. The archive material similarly supports the discussion of the case study —one of the largest preserved German roofs constructed with de l'Orme's method— providing details of the work programme and of authorities and individuals involved in its administration.

Technological progress and the 18th-century energy crisis

In 1797 David Gilly (1748–1808), chief of the Prussian building administration, published a book about curved plank roofs. He not only presented Philibert de l'Orme's invention to a greater number of experts, figure 1.[3] He also propagated building such roofs and developed on de l'Orme's construction principles. His main argument for the use of this 'new' construction was the reduction of needed timber.

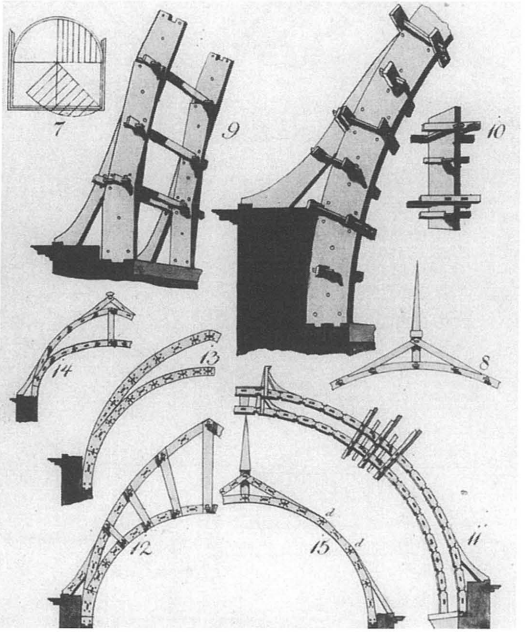


Figure 1
Gilly 1797 (fig. 5)

However, Gilly was not the first to use this economical argument for the introduction of a new construction method for roofs. Friedrich August Krubsacius (1718–1808), Professor of architecture at the Academy in Dresden, in 1784 had already published his invention of a new roof construction system, figure 2. Inspired by William Chambers' treatise on Chinese architecture, he proposed to build a roof without rafters. The Chinese roof seemed to him to be an accumulation of horizontal wooden beams and a simple construction. But he criticized its need for a large quantity of material. Moreover, it was only practicable for small span widths and the attic could not be used. Consequently, he imitated only one aspect, that of the limitation of the construction on purlins:

> Therefore I do not demand for the construction of a roof more timber, than a certain number of beams, which will lay on two strong stepped end walls up to the ridge. On the edges of the beams I will fix strong laths . . . and nail roof battens on them, this way the roof will be finished except for covering.
> For this no rafters and harmful eave boards, no collar beams, span pieces, top beams, struts, angle hinges, gable posts, wall plates, pole plates, . . . king-post or leaning roof trusses including their walls, yes, not even structural beams . . . are necessary. Doesn't this mean saving enough timber?[4]

David Gilly in his treatises about the plank roof also argued with the reduction of needed material.[5] With exemplary calculations he showed how much less timber —about one-third less— would be needed for a plank roof in comparison to traditional constructions. Moreover, he stressed that only short planks are used, so that valuable tree-trunks must not be touched. Carl Gotthard Langhans (1732–1808), who was not only the architect of the Brandenburg Gate in Berlin, but also the constructor of the first plank roofs in Prussia,

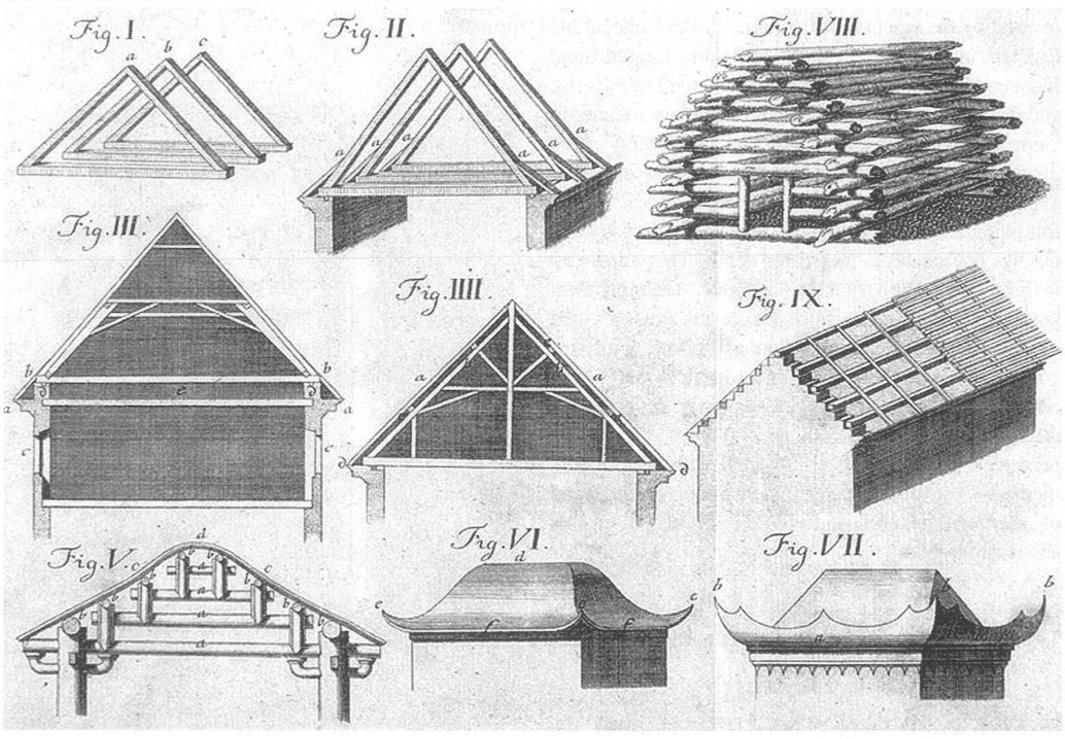


Figure 2
Krubsacius 1784 (fig. 2)

already operated with this method of argumentation, which emphasized the economic aspect by offering 'proofs' with calculations. He compared the dome of St. Blasien in the Black Forest (erected in 1777 by Nicolas de Pigage as a traditional wooden construction) and his alternative project with the rediscovered method of de l'Orme.[6] This allowed him to show that the consumption of timber could be reduced by more than 70 %.

Prussian plank-roof propaganda was strongly related to a new esteem of rural architecture (*Landbaukunst*). Plank roofs were especially recommended for barns and other (rural) buildings, which needed a big attic. Since the development of bureaucratic structures for royal buildings an instrument existed to enforce the aims of settlement policy in the field of architecture. Farmhouses and barns were no longer only vernacular architecture, but building types that the representatives of the royal building administration had to take care of. In terms of the theorization that took place in construction methodologies, pisé-construction must be mentioned alongside the use of plank roofs. As with the reinvention of the plank roof, the revival of building with loam started in France and is related to François Contereaux. David Gilly was again the most important German advocate. His argument was similar: He was convinced that by using cob walls timber could be saved, not only in the construction itself but also in the reduced requirement for heating material because of better insulation.

But was the argument for decreasing the consumption of timber more than a topos?

The arguments of Krubsacius, Langhans and Gilly —all of whom tried to introduce new and different roof construction methods— were based neither on structural arguments (firmitas), nor on aesthetic arguments (venustas), but mainly based on saving timber. Certainly the reduction of costs was attractive to both private customers and the Prussian or Saxon states. But the attentiveness to this argument signifies more than a concentration on the economic aspect. Krubsacius and Gilly could both count on a contemporary awareness of wood scarcity. In the 18th century German literature and newspapers we find many treatises and articles that present inventions to decrease the consumption of timber. These discussions were primarily related to ovens and other heating systems. The genre of timber-saving literature (*Holzsparliteratur*) culminated during the 1790s following the French Revolution. A general feeling of crisis may have been the background. Through these publications the scarcity of timber —more often caused by commercial legislation and transportation problems than by forestry— became a widely known problem discussed by representatives of the Enlightenment.[7] This also cleared the ground for architects to depart from the Vitruvian arguments and address them in the context of an existing discussion. Technological innovations and new construction methods became the subject of architectural scholarship.

A new roof for the castle of Augustusburg in Saxony (1797–1801)

The reception of Gilly's treatise is exemplified at castle Augustusburg in Saxony, which was originally constructed between 1568 and 1573 by Hieronymus Lotter, figure 3. By the end of the 17th century the Saxon Electors no longer regularly spent their summers at the castle. As a result the building went to ruin. The decay was accelerated by several constructional elements —such as the valleys of the pavilion roofs— and also by the topographic situation. Standing on the top of a hill the building suffered from the strong winds. Unfortunately on the outside walkways the lead sheets, which lay under floor plates of sandstone, were taken away during repairs in 1670. One consequence was that the entering rain damaged not only the brick walls.

The decay of castle Augustusburg in the 18th century

The subsequent stages of increasing decay and of the final repair between 1797 and 1801 are documented by rich archive material. In the Sächsisches Hauptstaatsarchiv three dossiers are conserved. They give an insight into the various attempts to repair the roof.[8] The drawings one can find at the archive of the Landesamt für Denkmalpflege Sachsen in Dresden and the repair work can be analyzed through a documentation of the existing roof.

In the second half of the 18th century dozens of notices detailing the poor condition of castle Augustusburg were received by the responsible

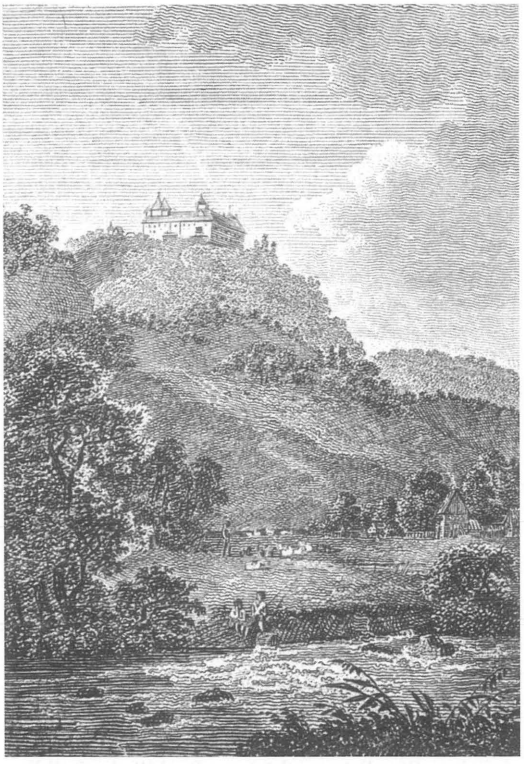


Figure 3
Castle Augustusburg around 1810. Copperplate engraving by Adolph Johann Darnstedt after a drawing of Adrian Zingg

authorities in Dresden. In 1782 because of financial problems a repair was limited to those buildings, which were actually used: the church and the administration building in the back courtyard. Only nine years later Landbauschreiber Christian Adolph Franke had to warn again. In the case that there should not be enough money granted to repair the whole structure he proposed different variants of demolition, starting from the partial demolition of two pavilions extending to a total demolition of three pavilions and their connecting buildings. But the financial resources were too small even for the realization of the demolition and all works were postponed. [9] The decay continued unabated and in 1797 Gotthold Christian Kaden, the responsible administrator, felt himself forced to inform the authorities in Dresden that:

> the castle of Augustusburg . . . is that much damaged, and also that the roof is that much damaged, that some wings could not be entered without fear of danger to life, because of the entering rain and snow, which made the major part of ceilings and floors rot and crash, not only the access to the administration building, but also to the church inside the castle is very dangerous when strong winds are blowing because of the apprehended collapse of the roof and of the very high chimneys. With this state of the castle, for which he as administrator is responsible, he can no longer take this responsibility and even with all performed vigilance he could not prevent the theft of the often falling down copper and iron, because the administrator's house is located a distance away.[10]

Whether it was the sum of these alarming notices or the impact of one certain notice that led to a fast reaction of the authorities cannot be verified today. But the Landbauschreiber Samuel Rößler was appointed to inspect the construction. He proposed to take away all copper and iron as quickly as possible to avoid the otherwise ongoing problem of theft. Further on, he again took up Franke's proposal for demolition. Rößler suggested to destroy the four pavilions, noting, that the reclaimed building material could be reused or sold. The repair of the connecting buildings would allow them to be used for storing this building material. The responsible authority gave its permission, but left the decision to the Elector Friedrich August. He ordered a second expert opinion by the architect Christian Traugott Weinlig (1739–1799). Weinlig was charged to inspect the construction and to check whether the castle «could be conserved under a light roof».[11] Herewith started a new chapter of attempts to save the building.

A new roof for castle Augustusburg

In October 1797 Weinlig traveled to Augustusburg and inspected the construction together with the local carpenter and bricklayer. He came to the conclusion that the building could be rescued. The walls were found to be in a comparatively good condition and the damages to the vaults, which were caused by humidity, could be easily repaired. The reason for the damage was the shape of the roof, especially the valleys. Weinlig illustrated his proposals for rebuilding with eight coloured drawings —plans, sections and roof plans— which contrasted the actual state with the rebuilding-project. He proposed to

cover the walkways of the connecting buildings with a new roof. A simplification of the roof shape of the pavilion roofs could be realized by eliminating the problematic valleys. In his proposal he also referred to the «light roof», which the Elector had mentioned:

> Had not on one hand the expense, which the complete pulling down of the former roofs would cause, and on the other hand doubts about introducing a system, which is totally different from the one carpenters are used to, kept me off, I would have decided to propose the roof construction of posts or planks nailed together, instead of rafters, which Philibert de L'Orme invented already two hundred years ago and which was executed by him and in our days in Berlin on many buildings with good success. The Ober-Bau-Rath Gilly in Berlin has published a description of these roofs, which he calls *Bohlen Dächer* (plank roofs, italics added) and of their advantages some time ago.[12]

Weinlig demonstrated that he was very well informed on the newest developments: David Gilly's 'Ueber Erfindung, Construction und Vortheile der Bohlen-Dächer' was published one year before. He hesitated to emphatically propose a plank roof due to the cost of pulling down the roofs, a lack of confidence in the skills of the carpenters and the seemingly impossible task of making a precise estimate. In June 1798 the authorities forwarded his proposal to the Elector; they now rejected the demolition option and recommended to repair and to preserve the castle «as a monument of former times».[13] The authority also mentioned:

> that the remark in the report of the Hof Baumeister Weinlig about the roof system with curved posts or planks, with which the big dome of the Halle aux Bleds in Paris is constructed, in these days deserves special attention, and that because of the connected timber-saving for further projects, the authority [Geheimes Finanzkollegium] will take it into consideration, as this year it has already ordered the construction of a new harness-barn in the back courtyard of the electoral stables near Friedrichstadt with this system.[14]

The plank roof under discussion was erected in Dresden in 1798 and is probably the first example of the new roof construction in Saxony, it is to be noted that the first curved plank roofs had already appeared ten years earlier in Prussia.[15]

Nevertheless the preparation for alteration work in castle Augustusburg started at the end of the same year with the intention to repair the traditional rafters. The site-supervisor was Kaden, who took care that the craftsmen rebuilt the old roof carefully. The hope was that much of the timber and roof slate could be re-used for the repair work.

In May 1799 Weinlig, together with the carpenter Johann Carl Bergauer,[16] traveled to Augustusburg because Kaden had informed him that much more timber than expected was rotten. Aiming to keep within the cost schedule, Weinlig was forced to rethink the proposed repair. The final decision was made on the site on 30th May 1799. As far as possible the old rafters should be restored, but the new lean-to roofs, where formerly had been gabled windows, should now be constructed with plank rafters, which should also substitute for totally rotten rafters in other parts of the roof.[17] The most important argument was again the reduction of needed timber. Kaden also argued that it would be easier for the citizens, who had to fulfill their statutory building labour, to transport the short planks up the hill instead of heavy timber.[18]

The typical curved shape of plank roofs is not found at castle Augustusburg, and this may be the reason that Günter Hutschenreuther did not discuss this building in his 1957 thesis, which still gives the best overview of Saxonian plank roofs.[19] The 'new' construction can be seen at the lean-to roofs of the corner buildings, figure 4. Both the pavilion roofs and the roofs of the connecting buildings have traditional constructions. The plank rafters are connected to a tie-beam using a mortice and tenon joint and their upper part leans to a beam, that is part of a substructure, figure 5. The curved part is nearly a quarter circle. Long eave boards form the roof shape. The roof has a pitch of 44 degrees and covers the rooms below with a width of nearly 9 m. The planks are about 3 cm thick, 27 cm wide and 1.58 m long. A rafter is constructed by a set of six planks that is nailed to a set of five planks with their whole length and two half planks at the end. Only forged nails were used not wooden dowels. And there were many nails: at every joint not less than two, and between two joints not less than one. At the documented rafter we find 129 nails. Also noteworthy are the cross braces on three levels. The laths of 3.5 x 7 cm normally strut three plank rafters, figure 6.

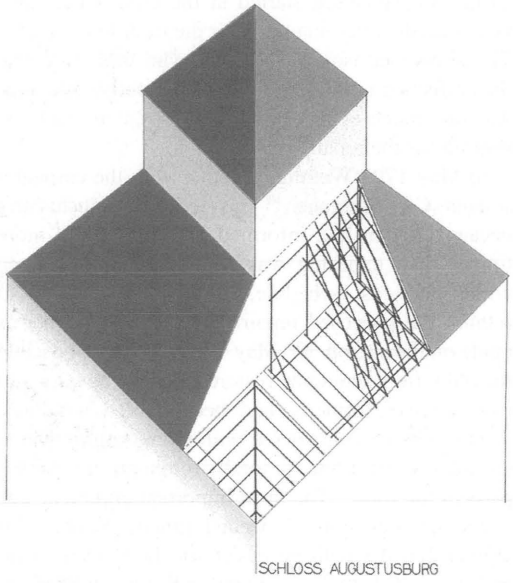


Figure. 4
Axonometric view of one pavilion of the castle Augustusburg. Drawing by the author

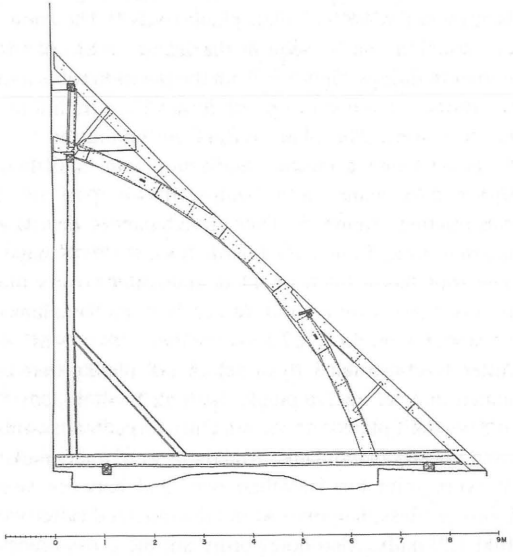


Figure 5
Typical rafter at the castle Augustusburg. Drawing by the author

Early lean-to plank roofs and the question of bracing

In his dissertation Eckart Rüsch estimated the existence of lean-to plank roofs as proof that this 'new' construction method was used for nearly all roof shapes and documented the development of this construction in Prussia.[20] Gilly's 1798 proposal is one of the oldest examples. He suggested to construct this plank roof with quarter-circular rafters, jointed to posts at the level of the ridge. Bracing is lacking, but Gilly recommended the construction of a strong wall able to take the shear forces of the rafters. No preserved example of these early lean-to plank roofs without bracing is known, so that we can assume that all of them broke down because of structural damages. But the Saxonian example, which was



Figure 6
Typical rafter at the castle Augustusburg. Photograph by the author

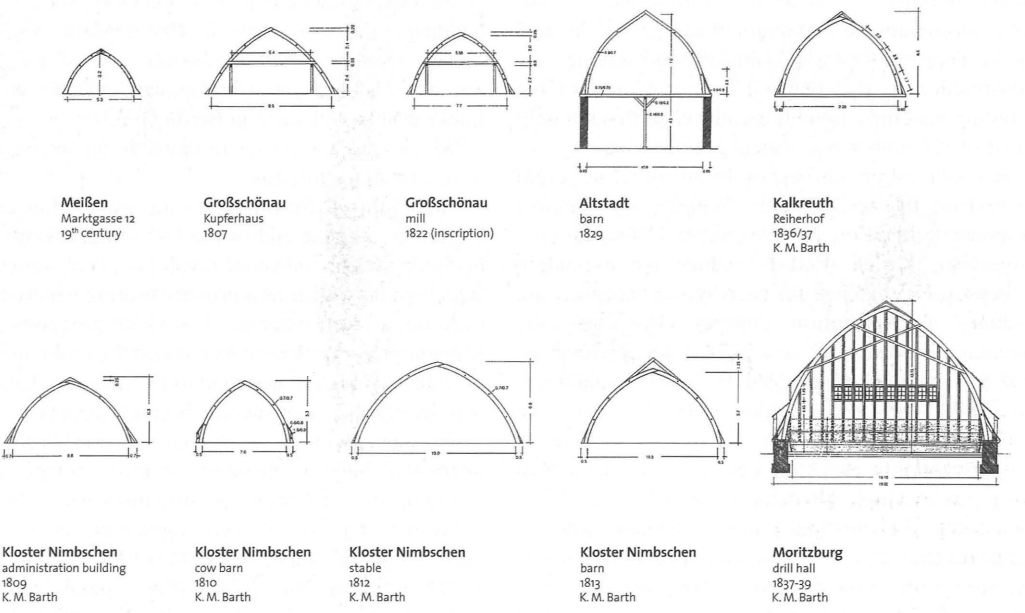


Figure 7
Saxonian curved plank roofs with bracing. Drawing by the author after Hutschenreuther 1957

designed only one year later, still exists. The cross braces between the plank rafters seem to fulfill their structural function and provide steadiness. Even if the quick reception of the construction method in Saxony can be estimated as a success of the Prussian propaganda, it should be accentuated that this reception was characterized by a critical approach and independent further development. Documentary evidence provides an unpublished treatise written in 1798 by Weinlig.[21] It demonstrates not only Weinlig's profound study of Gilly's publications during the construction of the new roof of castle Augustusburg, but also a critical attitude towards specific details and his attempts to improve them.[22] From this document we also learn that the first Saxonian plank roof over the harness-barn, of which the architect is unknown, diverged from Gilly's proposals. It was «strut only with laths and due to this achieved a nearly imperturbable steadiness».[23] It is probable that Weinlig's decision to brace the roof of castle Augustusburg traces back to the early example in Dresden. Perhaps it also resulted from a study of the treatise of Philibert de l'Orme, from which Gilly had reprinted the figures. Whatever caused a divergence from the Prussian model, whether it was the experience of carpenters and architects or a study of the French prototype, the bracing initiated an autonomous development in Saxony.

The classification of some Saxonian plank roofs — all of them with bracing— has caused problems until now, figure 7. [24] Most were designed by Karl Mildenreich Barth. Barth, who became Landbaumeister in 1816, certainly knew the plank roofs that had been erected by the building authority: both the example in Dresden and the roof of castle Augustusburg. It may be that he was even familiar with Weinlig's unpublished treatise. It is obvious that the bracing of plank roofs in Saxony goes back to the first examples and is correlated to a discourse taking place in the building authority, led by Weinlig.

The expensive repair

The repair of castle Augustusburg, which was finished in 1801, cost more than expected. There were

many attempts to stick to the estimate and to «take into consideration a maximum of savings».[25] As well as the decision for the presumed timber-saving roof construction, it was planned to re-use most of the building materials. Soon it became clear that not only most of the timber was rotten, but also that the roof slate could not be used again. In this difficult period of revising the cost schedules Weinlig, the architect responsible, died on 25th November 1799. The site-supervisor Kaden tried to reduce the exploding expenses. He searched for near-by slate quarries and reduced transportation charges. However, the alteration work finally cost 9272 Taler, 1 Groschen and 5 Pfennig, which doubled the expected amount.[26] In 1800 the responsible authority sent the Landbaukomissar Wilhelm Traugott Verlohren to Augustusburg to check the estimates. He exonerated Weinlig because the damage, which caused the increasing costs, would not have been visible when he made his first appraisal. Verlohren's only critical note referred to the nails used to fix the planks together. They caused an unexpected expense of some hundred Taler.[27] The authority did not forward this particular comment to the Elector.[28] This may have been, because the critique concerned the plank roof construction itself, a construction with which considerable timber saving was associated. If timber saving was more important to enlightened financial administrators than an economic use of nails, and somehow led to a tolerance of rising cost, one can probably diagnose a 'timber saving ideology'.

Conclusion: The decline of a fashion

The case study of castle Augustusburg has shown that in German countries the revival of de l'Orme's construction method was not limited to specific building types, e. g. barns and drill halls, which took an important place in Prussian propaganda. The timber-saving construction was also used for roofing churches and castles, even if it is to admit that in the case of castle Augustusburg the decision for the plank roof was the last possibility to save the building considering the financial situation. The range of built roof shapes and of construction details is richer than a study of the treatises would lead one to expect. Nevertheless by the 1830s the construction method had already lost its importance, even if we know of plank roofs that were constructed at the end of the 19th century, such as the building of the co-operative La Obrera Mataronense in Mataró (Antoni Gaudi, 1878–82), and of the 20th century. The latest known German example is the Luckenwalde settlement in Berlin (1932).

Which were the causes responsible for the decline of this roof construction?

The argument for timber saving was no longer as important as at the end of the 18th century. With the beginning of the industrial revolution, coal started to substitute for timber as a primary heating material. In addition, a rationalization of working processes and technological developments reduced the consumption of timber. Finally, transportation systems changed and the transport of materials became cheaper.

The main factor, however, was that iron became an alternative building material for roofs, bridges and greenhouses —all those constructions we associate today with the rise of civil engineering in the 19th century. Indeed, the second dome of the Halle au blé, which replaced the burned-down plank roof in 1811/12, was an iron construction by Belanger and Brunet. But also new constructions were developed, such as the Emy-system (1819), a mixed timber-iron structure:[29] Customary planks were horizontally laminated, curved with the help of a template and connected with iron plates and bolts.

But there were additional causes for the decline of plank roofs, that were related to the construction itself. One problem of this system was the cost — castle Augustusburg seems to be an example. In 1845 Gerhardt compared estimates for the erection of a traditional rafter roof and a plank roof— a method with a long tradition remembering Langhans and Gilly. He came to the conclusion that the limited use of plank roofs for the construction of agricultural buildings is a result of the fact that they are «not cheaper, but more expensive».[30] Another factor, as well as the structural deficiency of the early examples, was the skeptical attitude of carpenters. Even if the construction of plank roofs was part of the exams of craftsmen in Prussia —a consequence of the Prussian propaganda— carpenters disliked the construction method because of a higher rate of accidents during the erection.[31] A construction that is not accepted by the craftsmen will never become vernacular. But before mechanization took command vernacular constructions were the most successful in terms of survival of form over long periods.

Notes

I owe debt to many people, who supported me, especially archivists, librarians and the staff of castle Augustusburg. I want to thank Andreas Tönnesmann for encouraging me to write this report, Jane Harrington for her support with the English version, Lothar Schmitt for being always available, when computer problems made me feel desperate, Irene Lindemann for her emphatic support of the documentation on site and Daniela Mondini for her endless patience with me.

Concentration on German countries means that nearly all (archive) sources and research reports are written in German. I decided to translate the cited parts and give the original version in the notes.

1. The roofs of the Rue de Rivoli in Paris became famous (Szambien 1992, 78–119, concentrated on the urban aspect but gave a lot of figures). In 1803 the fashion had even arrived in the United States of America with the discussion about the roof of the Hall of Representatives of the Capitol in Washington (Norton 1977, 67–68; Deming 1984, 184). The roofs constructed by Christopher Wren provide examples of the use of de l'Ormes method outside France before the erection of the Halle au blé (Yeomans 1992, 57).
2. See for example Graefe 1985, Graefe 1989, Schmidt 1989, Spohn 1989, Rüsch 1995.
3. Gilly (1797) gives a summary of de l'Orme's 'Nouvelle Inventions' of 1561. For de l'Orme's treatise see also Pérouse de Montclos 2000, 107–121.
4. Krubsacius 1784, 16: «Ich verlange daher zu einem Dach kein mehreres Holz, als eine gewisse Anzahl Dachbalken, die sich auf zwey starken Giebelwänden stufenweis über einander bis an den Forsten erheben. Auf den abgeschärften Kannten derselben, will ich starke Latten, oder halbe Pfosten, zwey Ellen weit von einander, längs herab mit Schwänzen einlassen, und auf diese die Dachlatten nageln: so wird das ganze Dach, bis zum Eindecken, fertig seyn.
   Hierbey sind keine Sparren und schädliche Anschieblinge, keine Kehlbalken, Spannriegel, Hahnebalken, Streben, Winkelbänder, Giebelsäulen, Mauerlatten, Ober— und Unterschwellen, stehende und liegende Stühle, sammt ihren Stuhlwände, ja, sogar keine Hauptbalken . . . nöthig. Heißt das nicht Holz genug ersparet?»
5. Beside the publication of 1797 Gilly took on the argument in 1799 and added the treatise about plank roofs to the later editions of *Handbuch der Land=Bau=Kunst*.
6. Nicolai 1796, Beylagen, 27–34 and fig. III (cited by Gilly 1797, 50–59).
7. Radkau 1983, Radkau (1986) even diagnosed an «alleged 18th century energy crisis».
8. SächsHStA, loc. 35803, Rep. VIII, Augustusburg 23; SächsHStA, loc. 35803, Rep. VIII, Augustusburg 24; SächsHStA, loc. 492.
9. For the notices about the decay see SächsHStA, loc. 492, 1–12 (Report of Geheimes Finanzkollegium, 21st June 1797).
10. SächsHStA, loc. 492, 5^{v} – 6^{v} (Report of Geheimes Finanzkollegium, 21st June 1797): «daß das Schloß zu Augustusburg . . . dergestalt beschädigt worden sey, daß . . . auch die Dachung dergestalt schadhaft sey, daß ohne zu befürchtende Lebens Gefahr einige Flügel gar nicht mehr zu betreten wären, immassen durch das eindringende Regen und Schnee Wetter, die Decken und Dielen größtentheils verfaulten, und herunterstürzten, wie den auch der Zugang zur Justiz und Rent Amts Stube . . . , als auch in die im Schloße befindliche Kirche . . . durch den drohenden Einsturz der Dachung, und Herabstürzung der sehr hoch angebrachten Feuer Oeßen bey starken Winden sehr gefährlich wärn. Bey dieser Beschaffenheit, des ihm als Rentbeamten pro Inventario mit übergebenen Schloßes . . . , könne er vor solches nicht weiter stehen, noch bey dem öfftern Herunterstürzen wegen der Entlegenheit der Rentbeamten Wohnung, die Entwendung von Kupfer und Eisen mit aller angewandten Vigilanz verhüthen.»
11. SächsHStA, loc. 492, 43^{v} (Elector Friedrich August, 2nd October 1797): «allenfalls unter einer leichten Bedachung und durch sonstige schickliche Veranstaltungen conserviert werden könne».
12. SächsHStA, loc. 492, 66^{r} – 67^{r} (Report of C. T. Weinlig, 12th April 1798): «Wenn mich nicht auf einer Seite die Betrachtung jenes Aufwandes, welche die gänzliche Abtragung der damaligen Dächer erfordert, auf der andern aber die Bedenklichkeit, eine Bau Art, welche so sehr auser der Sphäre der an ihr altes System gewöhnten Zimmerleute liegt, auf die Bahne zu bringen, abgehalten hätte, so würde ich mich entschloßen haben, die bereits vor zweihundert Jahren von Philibert de L'Orme erfundene, und von diesem, und in unsern Zeiten zu Berlin bey mehrern Gebäuden, mit gutem Erfolg ausgeübten Dach-Verbindung von zusammen genagelten bogenförmigen Pfosten oder Bretern, statt der Sparren, in unmaasgeblichen Vorschlag zu bringen. Der Geheime Ober Bau Rath Gilly, zu Berlin, hat eine Beschreibung dieser Dächer, welche derselbe Bohlen Dächer nennt vor einiger Zeit herausgegeben, und das Vortheilhafte derselben umständlich angezeigt.»
13. SächsHStA, loc. 492, 57^{v} (Report of Geheimes Finanzkollegium, 20th June 1798): »als ein Monument älterer Zeiten, voritzt in Dach und Fach herzustellen und erhalten zu laßen.» This is obviously less connected with the idea of protection of historical monuments as it developed around 1900 but a sign of castle Augustusburg's value for the dynastic memory.

14. SächsHStA, loc. 492, 57^{v} (Report of Geheimes Finanzkollegium, 20th June 1798): «daß die von dem Hof Baumeister Weinlig in seiner Anzeige gemachte Bemerkung über die Dachverbindung mit bogenförmigen Pfosten und Bretern, nach welcher auch das große Kuppeldach der Halle aux Bleds zu Paris construirt ist, in dermaliger Zeit, besondere Aufmerksamkeit verdient, und es wird das Geheime Finanz Collegium auf Anwendung dieser Bau Art in Rücksicht des damit verbundenen beträchtlichen Holz Ersparnißes bey vorkommenden darzu schicklichen Fällen, thunlichsten Bedacht nehmen, wie den auch bereits im heurigen Jahre, die Erbauung eines neuen Geschirr-Schuppens bey Ihro Chur Fürstl. Durchl. ohnweit der Friedrichstadt gelegenen neuen Ställen, im hintern Hofe, nach dieser Bau Art, angeordnet worden ist.» The harness-barn in Dresden, which was constructed in 1798, does not exist any more. The authority probably knew of the construction of the Halle aux blé since 1796, because in this year Carl Gottlob Dähne published an article about it in the 'Anzeigen der Churfürstlich Sächsischen Leipziger ökonomischen Societät'; Dähne 1796. Two members of the authority — Peter Carl Wilhelm Graf von Hohenthal and Andreas von Wagner— were also associated with the society in Leipzig.
15. Rüsch (1995), catalogue no. 1, 2, 20, 28.
16. Johann Carl Bergauer was 'Hof-Zimmer-Polirer' —foreman of the carpenters— at the electoral building authority.
17. SächsHStA, loc. 35803, Rep. VIII, Augustusburg 24: specification of the travelling expenses and 'site record' (31th May 1799): «wegen vortheilhafter Ausbeßerung des Sparrwerks aufs neue berathschlagt, und beschloßen, daß soweit es möglich die Sparren, durch Abschneiden u. Anstumpfen erhalten, die neuen Stücken Dach, wo vordem die Erker gestanden, von Bretbügen gefertiget, und diese Art von Dächer, in der Folge, an Stellen, wo die alten Sparren keine Ausbeßerung erlaubten, anzubringen.»
18. SächsHStA, loc. 492, 78^{r} (Report of Geheimes Finanzkollegium, 16th July 1800): «beträchtliche Erleichterung der Baudienste für die Amts-Unterthanen, welche zum Theil leichtere Bretfuhren statt der schweren Bauholzfuhren den Berg hinauf zu thun . . . haben.»
19. Hutschenreuther 1957. I used the copy of the Sächsische Landes— und Universitätsbibliothek in Dresden.
20. Rüsch 1995, 67.
21. SächsHStA, loc. 34565, Rep. XLI, Gen. 475. Because of the shortened autograph [C. T. Wlg.] and the chronological coherence this description, which dates from 12th September 1798, may be attributed to Weinlig.
22. Weinlig proposed —opposing Gilly— to erect the rafters and cog a thinner ridge beam.
23. SächsHStA, loc. 34565, Rep. XLI, Gen. 475: «blos mit Latten verriegelt, und hat hierdurch eine fast unerschütterliche Festigkeit erhalten.»
24. Rüsch 1995, 44, Note 198: «die Einordnung einer Reihe sächsischer . . . Bohlendachbauten wegen konstruktiver Eigentümlichkeiten ungeklärt»
25. SächsHStA, loc. 557, Vol. VII, 99^{v} (Die Einrichtung des Ober-Bauamts betr., 3rd January 1798): «auf möglichste Ersparniße Rücksicht genommen». This instruction was valid for all electoral building affairs.
26. SächsHStA, loc. 492, 68^{r} (Report of C. T. Weinlig, 12th April 1798): Weinlig estimated —beside the needed timber— 5834 Taler, 14 Groschen and 4 Pfennig.
27. SächsHStA, loc. 35803, Rep. VIII, Augustusburg 23, 226^{v} –227^{r} (Report of W. T. Verlohren, 4th July 1800): «und da nach Angabe offt gedachten Ober Landbaumeisters Weinligs statt der in den Stuhl Dächern befindlichen Sparren und übrigen Dach Verbindungen die vorerwähnten Brethbügen aufgesezt wurden, so erfordern solche nicht nur der mühsamen Arbeit wegen weit mehrere Zimmer Arbeits Löhne, sondern da solche auch ganz neu abgeschaalt werden müßen, weit mehrere Nägel . . . und dergleichen. Dies alles würde zwar das gnädigst bewilligte Quantum . . . um mehrere Hundert Thaler übersteigen . . .».
28. SächsHStA, loc. 492, 76^{r} – 84^{r} (Report of Geheimes Finanzkollegium, 16th July 1800).
29. Meschke 1989, 105–107; Gould 2001, 76–78; Yeomans 1992, 199. The Emy-system was often used for railway stations, e. g. that of Munich (1848) and the more famous King's Cross Station in London (1852). Normally the arches supported saddle roofs.
30. Gerhardt 1845, 106: «die geringe Anwendung der Bohlendächer bei Landwirthschafsgebäuden erkläre sich einfach daraus, weil sie n i c h t w o h l f e i l e r, sondern t h e u r e r, wie geradlinige Sparren— oder Satteldächer seien . . .». I owe my debt to Ulrich Maximilan Schumann, who drew my attention to this article.
31. Gerhardt 1845, 107 (accidents), 112 (exams).

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SächsHStA, loc. 492: Die Wiederherstellung der Schloßgebäude zu Augustusburg betr., Ao. 1797 sq.

SächsHStA, loc. 34565, Rep. XLI, Gen. 475: Beschreibung eines von breternen Bügen, statt der Sparren, zu errichtenden Sparrwerks, und der hierbey, bey dem Zulegen und Aufrichten derselben erforderlichen Behandlung.

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Analysis and building process of hidden wooden frameworks in 17th century Spanish treatises

Rafael Hernando de la Cuerda

Although the Treatise called *«Breve compendio de la carpintería y tratado de lo blanco, con algunas cosas tocantes a la Iometria y puntas del compás»* [Brief course in fine woodwork, including issues concerning Geometry and compasses] by Rodrigo Álvarez has not been dated accurately, it probably appeared some time after the publication of the Treatises (first and second books) written by Fray Lorenzo de San Nicolás, called *«Arte y uso de Architectura»* [The Art and Use of Architecture] in 1639 and 1664.

This research work focuses on the analysis of the wooden structures described in both treatises, which are built to cover large areas and designed to remain hidden after the construction is finished.

By using this method, great differences in the way to approach the inside and the outside of the building may be achieved, and regardless of the type of supportive structures, new architectural solutions may appear, such as *false vaults made of light materials* and *spires*, which, in both cases, are supported by hidden wooden frameworks. Thus, apart from the fact that they are made of wood, the formal aspect acquires a special significance when defining such elements.

False vault of light materials

> It is one that, without a constructive function, is fictitiously made of wood and covered by plaster. (J. M. Paniagua)
>
> Rib-spreading skeleton of a building, where a light lathing or raddle is fixed, which generally acts as support for a plaster decking. (E. Nuere)

Spire

> Pyramid-shaped member, which may sometimes be conical or bulbous in form, that finishes as a very sharp arrow and culminates a tower. It may have a stone structure, but it is usually made of lead or slate-plated wood. (J. M. Paniagua)
>
> Framework with a regular polygonal base that finishes off a tower. Cupola framework with lantern, the intrados or soffit of which is generally covered following the technique used for creating false vaults, employing light materials, such as wood. (E. Nuere)

In the latter definition, the two types of architectural solutions, known as spires, are distinguished:

— That which is used to cover and crown a tower, a solution that was imported from Burgundy and was introduced in Spain in the 16th century.
— The model that resolves the problem of an important cupola with a lantern, the inside finishing of which is similar to that of the false vault with a light lathing or raddle, which generally acts as support for a plaster decking.

The fact of being apparently subordinated to ornamental motifs is the reason why these structures have not been thoroughly studied, despite of their

significance. There are two other features that have certainly influenced this fact: they are difficult to access and due to the fact that they are hidden, sometimes they have lacked the proper maintenance, and in many cases, specially from the 19th century onwards, when the need to renovate such structures arose, wooden frameworks were simply substituted by metallic structures. The result is that the original structure no longer exists.

It is important to consider whether the structure is an imported model, or a part of the tradition of the *fine woodwork carpenters*.

In this paper, I analyze several of the chapters that deal with the wooden structures at hand and which are defined in some of the Spanish treatises of the 17th century. The Treatise written by Fray Lorenzo de San Nicolás describes two kinds of spires, and that written by Rodrigo Álvarez focuses only on the model based on a cupola with lantern. A subsequent treatise by Juan García Berruguilla (1747) also deals with a model that is based on a cupola with lantern.

In order to gain a deeper knowledge on this field, I think it is absolutely necessary to study on location some of the structures that were built at the same time in which the Treatises were published. By doing this, I have been able to experience by myself how difficult it is to access buildings, both physically and otherwise, in which those structures were used, and the large number of them that were substituted by their metallic versions.

The Treatise by Fray Lorenzo de San Nicolás

The treatise written by Fray Lorenzo de San Nicolás was published in two volumes. The first one appeared in 1639 and the second one in 1664. The first volume has eighty-three chapters and the second volume is composed of seventy-one chapters. Both volumes cover a wide range of issues. The first volume —from chapter 46 to chapter 49— deals with woodwork; the same topic may be found in the second volume in chapters 50 and 51. I now proceed to mention the chapters in which woodwork is the main subject.

First volume

Chapter 46. On seasons in which to cut wood and the appropriate way to do so.

Chapter 47. On the way to trace frameworks and the different ways to do so.

Chapter 48. On framework cuts, bases and strengthening.

Chapter 49. On the way in which to cover frameworks.

Second volume

Chapter fifty. On two kinds of modern frameworks, which are very much decorated on the outside.

Chapter fifty-one. On another way of covering large or small Chapels with wood.

I refer to chapter 48 in the first volume, and chapter 51 in the second volume.

Chapter 48

On framework cuts, bases and strengthening. Figure 1

In this chapter, Fray Lorenzo de San Nicolás starts by describing three different types of frameworks.

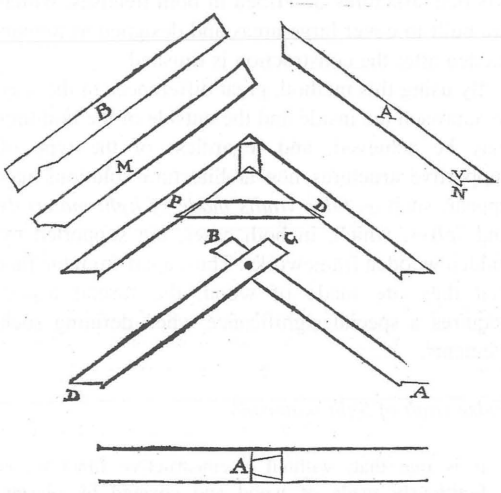


Figure 1
Types of frameworks defined by Fray Lorenzo de San Nicolas

— First, the *armadura a la molinera*, commonly known as single gable. He lists examples where the rafters protrude, thus forming an eave, and examples where the rafters reach the walls without protruding, and the different cuts that apply in each case (oblique cut or reduction of thickness).
— Framework formed by rafters and courses. There is a description of the cuts to be made, their names and proportions. As a reinforcement for the framework, the author speaks of a piece of timber that he calls brace, which may be defined as a horizontal beam, and includes the proportions, since it is explained that they shall be placed on the third portion of the rafters. The location of the rafters is also explained, as well as the part of the wood that allows a better performance, and the importance of an adequate execution. The reader is advised not to use valleys, whenever possible.
— *Armadura de tijera*, in which the rafters cross like scissors. The ends project over the joint on the upper portion, and are joined at the bottom by reducing thickness with an oblique cut. In book 4, chapter 2 of the Treatise by Vitruvius there is a reference to this type of framework, under the title *On Column Ornaments,* where it is explained how Architects imitated ancient wooden temples to erect stone and marble ones. Figure 2.

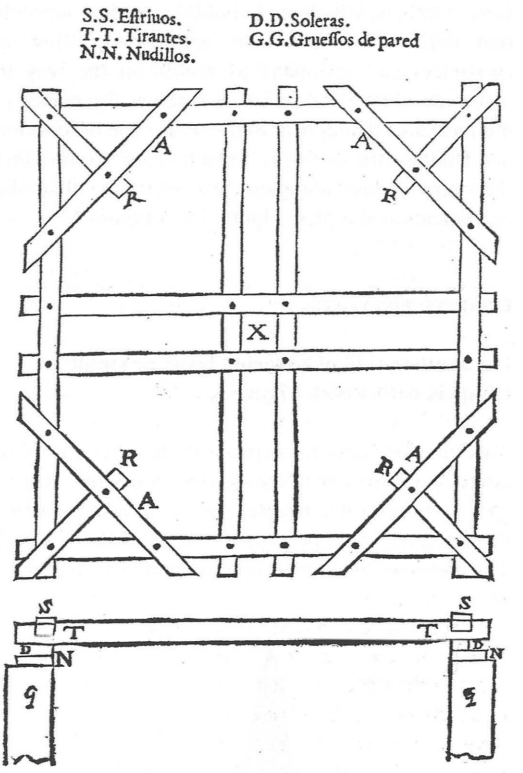


Figure 2
Anchoring of wooden frameworks on stone or brick constructions, as defined by Fray Lorenzo de San Nicolas

The chapter then continues with the explanation of the anchoring of wooden frameworks on the brick or stone constructions, by putting first some short and thick pieces of timber or horizontal beams, measuring two thirds of the width of the bearing wall, at a moderate distance from each other, of the same thickness as the wooden base. The evened bases are anchored on these horizontal beams to the inside of the wall. It also explains how to join the pieces of the base when necessary, and that this should be done on the horizontal beams. The ties rest at different lengths at the bases of both sides, according to each case. It may be necessary to include oblique timbers in the incoming angles, as well as diagonal timbers. The placement of evened buttresses into the wall is also explained, as well as the sizes and joints. Once the bases, ties and buttresses are fixed, and where appropriate, the oblique timbers in the incoming angles as well as the diagonal timbers, the framework is then ready to receive the pair of rafters or *tijeras*. It is said that the way to join the rafter to the buttress should be through an oblique cut. The author leaves the calculation of the size of all elements to the savoir-faire of the Master.

Apart from the oblique timbers in the incoming angles and the diagonal timbers, the crossed ties are also anchored on the spire, so that they form a square in the middle, where the main support, where the spire is strengthened, is anchored.

Strong winds are a great danger to spires. Therefore, certain proportions should be kept according to the width of the tower supporting the spire and the height. Fray Lorenzo highlights the need to include sloping pieces (hips, toral rafters, pieces that go from the base to the hip, and rafters) in an orderly manner, and in

large numbers, which are to hold the vertical supports that will stick out on the upper part, allowing carpenters and architects to decide on the way to distribute them. The author also refers the reader to the measures that appear in the scale. The description and study of the decisions to be taken when building the spire is less complete and methodic than the aforementioned topics. Figure 3 and Figure 4.

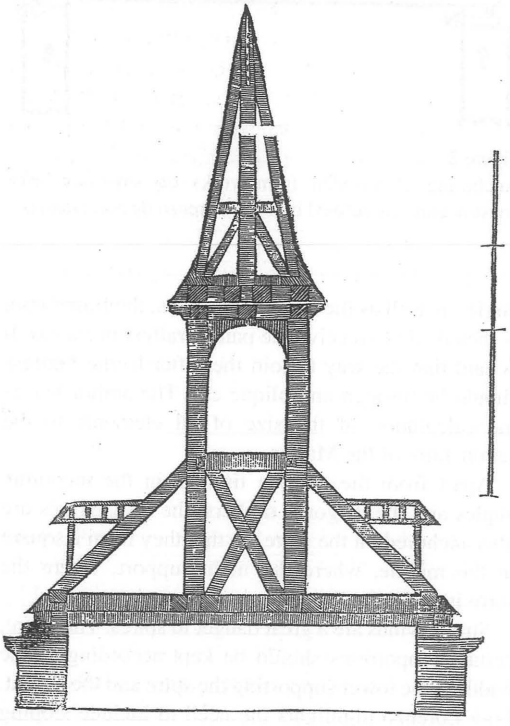
Chapter fifty-one

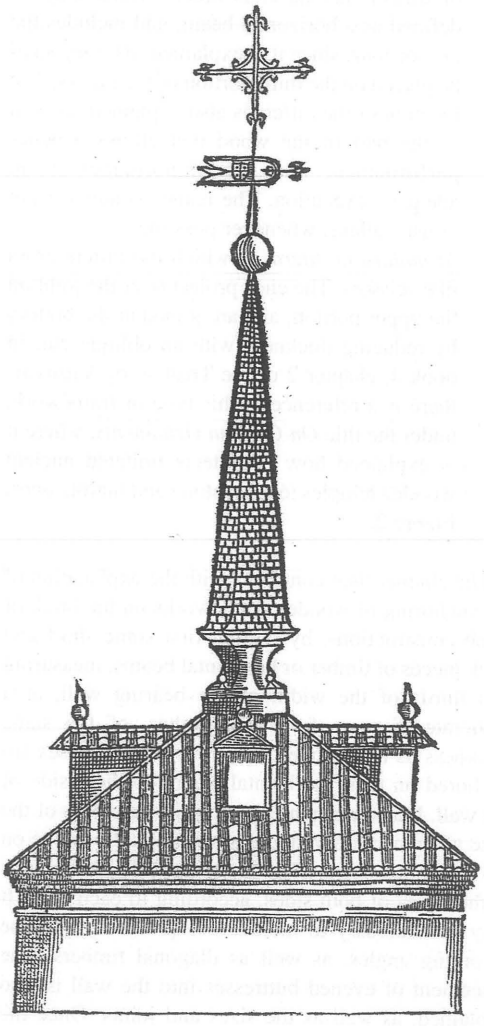
On another way of covering large or small Chapels with wood. Figure 5.

This chapter starts by explaining the advisability of covering Chapels with the cupola framework, that is, with a tower of a squared or octagonal base that finishes in a spire, or steeple, that is made of wood. The choice of wood over other materials is due to the reduction in cost, but it remains a secure and strong structure. It then lists some of the works carried out following such pattern: the first one by Father Francisco Bautista in Madrid, three works carried out by Fray Lorenzo, two in Madrid and one in Talavera, and one carried out by Fray Pedro de San Nicolás in Salamanca.

There is a description of the plan, which is circular inside, and chamfered on the outside, without ties.

It explains the way to place the evened horizontal





Figures 3–4
Types of spires, as defined by Fray Lorenzo de San Nicolas

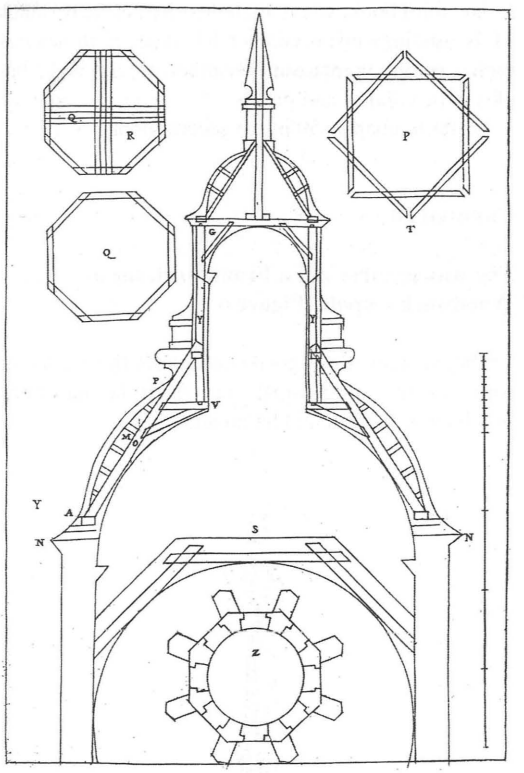


Figure 5
Cuopola framework with lantern, as defined by Fray Lorenzo de San Nicolas

beams into the wall; on them, the evened buttresses are placed in a chamfered square into the wall, and they are fitted together through indentations made half way through each beam so that the heads are left sticking out, as may be seen in the accompanying drawing. He recommends that these buttresses be thick, giving measurements according to the space to be covered; thus, for thirty feet, we should never place a buttress, the thickness of which is less than half a yard and a third, approximately, and it should always be resting on a board. Joints are achieved by nailing, in the first place, the beams with two pegs, and iron squares above; at least two thirds at each side should be well nailed. This is also reinforced with masonry and carpentry work. When doing this, we should be careful not to allow the lime to touch the wood.

The hips, toral rafters and the pieces that go from the base to the hip are anchored, and when the text says *deshiladas por los cantos*, I understand that they are not joined, because the pieces of timber that join the roof rafter and the ties are going to be used to bring them together. The thickness of the hips is determined by the spam that is to be covered, as well as that of the toral rafters and large pieces that run from the base to the hip, each of them being placed at each side of the hip. The remaining pieces from the base to the hip may have a smaller size, as described in the text.

The remaining upper chamfer is executed, and the roof angles and rafters are treated so that the width of the lantern is proportional to the total width to be covered. Bearing in mind the resistance of the structure (the size of the centering and the pieces of timber that join the roof rafters and the ties depends on the tracing), when tracing the proportions for the construction of the spire, the author states that in order to trace the rafters it is essential to have made a detailed real-sized drawing of the centering beforehand, as well as the *copada* of Point Y. The drawing is then drafted beginning at the central point; a minimum measurement for the centering is set, and the piece of timber that joins the rafter to the ties is thus fastened with wooden pegs both in the upper and lower parts of the centering, rafters, roof angles and the pieces that run from the base to the hip, with well adjusted and fixed chiseled joints. The result is a strong, firm structure with tied rafters.

The placement of the strengthening chamfer is the most important step. The text says that the eight chamfers receive the eight *toral* rafters, and that this strengthening chamfer is over two thirds of the *toral* rafter.

According to the drawing of the upper part on the right, marked with letter P., and in the empty space (T), there is a single *toral* rafter per breadth (in the axis). This is the only possibility for the *toral* rafters to fit into the T. This is not seen on the outside, since the finishing of all pieces is unified in form by timbers of different sizes that join the rafter and the tie. Eight braces are placed in such a way that they do not hinder the function of the real-size drawing of half the cupola. Above the strengthening chamfer, eight vertical joists are placed, the height of which corresponds to that of the lantern. The proportions of the lantern are discussed in the chapter so that it fits

within the whole structure, and these vertical supports are received in the chamfer (R).

The construction of the *cupulilla* (little cupola above the lantern), the spire and the horizontal bar of the Cross, which is fixed to the ties, is also described.

However, there is no explanation as to the function of the buttresses (Z) according to the structure of the lantern, but it relates it to decorative motifs. In a less structured way, the chapter explains the reader how to build some decorative motifs with iron squares, from large ornamental convex moldings to the eight vertical supports, and in the chamfers on which the moldings are fixed.

Fray Lorenzo explains several decorative motifs as well as inside and outside finishes, and how he is carrying out same in some of the works in which he is involved at the time of writing, explaining several of the steps he is taking. The chapter finishes by giving some advices to the Masters and apprentices.

Lastly, there are some graphics containing a vertical section of the chapel with a cupola framework with lantern and five horizontal sections, four of which correspond to the four structural chamfers which are necessary to assemble the decking (chamfer of the buttresses, the chamfer where the rafters of the cupola framework are fixed with an oblique cut, the strengthening chamfer and the chamfer of the upper part of the lantern and the base of the *cupulilla*. The fifth one corresponds to a lantern section cut, where we can see some flying buttresses and the windows of the lantern.

All drawings are inside a vertical rectangle, where a graphic scale is also included at the bottom right.

The Treatise by Rodrigo Álvarez

The manuscript, which apparently was not intended for printing, but for work and study, is composed of a dedication and three books.

The first book has 24 chapters and deals with the Architecture, materials, geometry, water and the means to guide it.

The second book starts in chapter 25 (there are two chapters numbered 38) and ends in chapter 50 and it deals with the building and formal characteristics of frameworks. It includes a description of the *carpintería de lazo* and a model of the spire of the cupola framework with lantern.

The third book, which includes chapter 52 (chapter 51 is missing) up to chapter 61, deals with several topics, including treatises on caliber, clocks, and a list of towns, villages and places.

I refer to chapter 50 in the second book.

Chapter 50

The way to carry out a Framework for a Woodwork Cupola. Figure 6

To begin with, Rodrigo Álvarez tells the reader of some of the spire works in which he has been involved in Madrid and Salamanca.

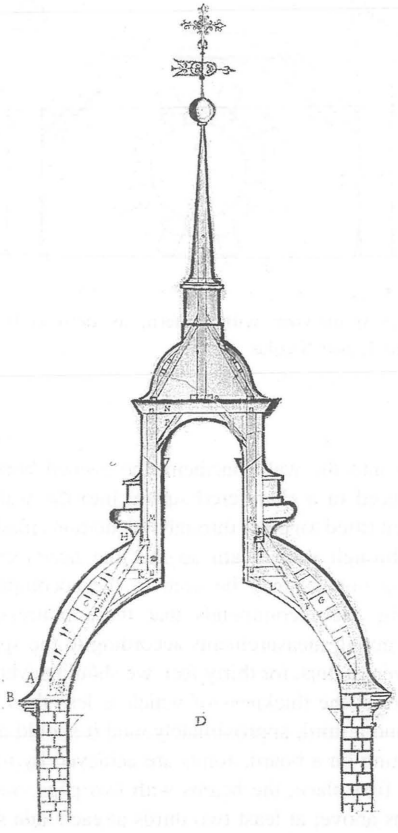


Figure 6
Cuopola framework with lantern, as defined by Rodrigo Álvarez

He then explains the way to place the evened horizontal beams at a distance not exceeding, approximately, one yard into the wall; on them, the evened buttresses are placed in a chamfered square into the wall, and they are fitted together through indentations made half way through each beam so that the heads are left sticking out. The author remarks that these shall measure half a yard, approximately, and the thickness shall be one third; they should be resting on a board, with large well-nailed *cogotes*, and with these nails bent at the bottom, and over them, the iron squares should be placed, at least two thirds being well-nailed on both sides. It is then reinforced with masonry and carpentry work. When doing this, we should be careful not to allow the lime to touch the wood.

The roof angles and the *toral* rafters are fixed by oblique cuts at the upper part to another chamfered beam. Afterwards, the roof angles and rafters are treated so that the width of the lantern is proportional to the total width to be covered. Bearing in mind the resistance of the structure (the size of the centering and the pieces of timber that join the roof rafter and the ties depends on the tracing), when tracing the proportions of the spire, the author says that in order to trace the rafters it is essential to have made a detailed real-sized drawing of the centering beforehand, as well as the *copada* of Point C. Then, the drawing is drafted beginning at the central point; a minimum measurement for the centering is set, and the pieces of timber that join the roof rafters and the ties are thus fastened with wooden pegs both on the upper and lower parts of the centering, rafters, roof angles and the pieces that run from the base to the hip, with well adjusted and fixed chiseled joints. The result is a strong, firm structure with tied rafters.

The placement of the strengthening chamfer is the most important step. The text says that the eight chamfers that receive the eight toral rafters, are on each side of the toral rafter, and that this strengthening chamfer is over two thirds of the toral rafter.

Eight braces are placed in such a way that they do not hinder the function of the detailed real-sized drawing of half the cupola. Above the strengthening chamfer, eight vertical joists are placed, according to the height of the lantern. The proportions of the lantern are discussed in the chapter so that it fits within the whole structure, and these vertical supports are received in the chamfer N.

The construction of the *cupulilla*, the spire and the horizontal bar of the Cross, which is fixed to the ties, is also described

Lastly, there are some graphics displaying a single figure that represents a vertical section of the spire of the cupola framework with lantern, which is folded in the manuscript, since it is bigger in size (279x197). The drawing, which is colored, contains the wooden pieces, with capital letters assigned randomly to specific pieces or to areas of the figure. The letters correspond to those referred to in the written text.

There is a scale at the bottom of the drawing.

Comparative analysis of the chapters described and extracted from the Treatises by Fray Lorenzo de San Nicolás and Rodrigo Álvarez

Chapter 48 of the first book in the Treatise by Fray Lorenzo de San Nicolás may not be compared to the Treatise written by Rodrigo Álvarez, since it does not focus on the same type of spires.

We may draw a comparison about the way to solve the building of a cupola with lantern, through the spire explained in chapter 51 in the second book of the Treatise by Fray Lorenzo de San Nicolás and in chapter 50 in the Treatise written by Rodrigo Álvarez.

Chapter fifty-one. Deals with another method of covering large or small Chapels using wood.

Chapter 50. On the way to carry out this Framework for this Woodwork Cupola.

The titles of both chapters are different, because Fray Lorenzo deals with the covering and building of spires in a much broader sense, and he even considers decorative motifs.

R. Álvarez explains more concisely the way to build the framework for a certain Woodwork Cupola.

Regardless of the works to which both authors refer as carried out by them, or which are in the process of being carried out, and which, evidently do not coincide, the rest of the written information is very similar in both books, the treatise by Fray Lorenzo de San Nicolás being more complete, methodical and detailed than Rodrigo Álvarez's. The text by Rodrigo Álvarez seems to have been copied from the former, obliterating some parts of the text and simplifying some of the descriptions:

In the treatise by Fray Lorenzo the sizes of the pieces are referenced proportionally to the lights to be covered; in the treatise by R: Álvarez minimum measures are given.

When describing the way to operate with the rafters between the first and second chamfer, the explanation of the members to be placed is simplified.

The whole explanation of the different aesthetic finishes and the decorative motifs, both on the outside (including the flying buttresses) and the inside, is only included in the text written by Fray Nicolás. Likewise, the explanation on how to build certain decorative motifs with iron squares, which go from the large ornamental convex moldings to the eight vertical supports, and in the chamfers on which the moldings are fixed, only appears in Fray Nicolás' text.

Lastly, the advices to Masters and apprentices, and the description of some operations appear only in the treatise by Fray Lorenzo.

Graphics are different in both texts. The vertical section in the treatise by R. Álvarez is more elaborated than that in Fray Lorenzo's, although the latter shows five additional horizontal sections, among which the one concerning the strengthening chamfer is especially helpful to understand what is written for building purposes.

The wooden pieces are thicker in the treatise by R. Álvarez.

Regardless of the differences in the way in which the information is displayed, there is a significant difference in the contents of both treatises. Figure 7.

The relationship among the upper chamfer where the rafters of the cupola are fixed through an oblique

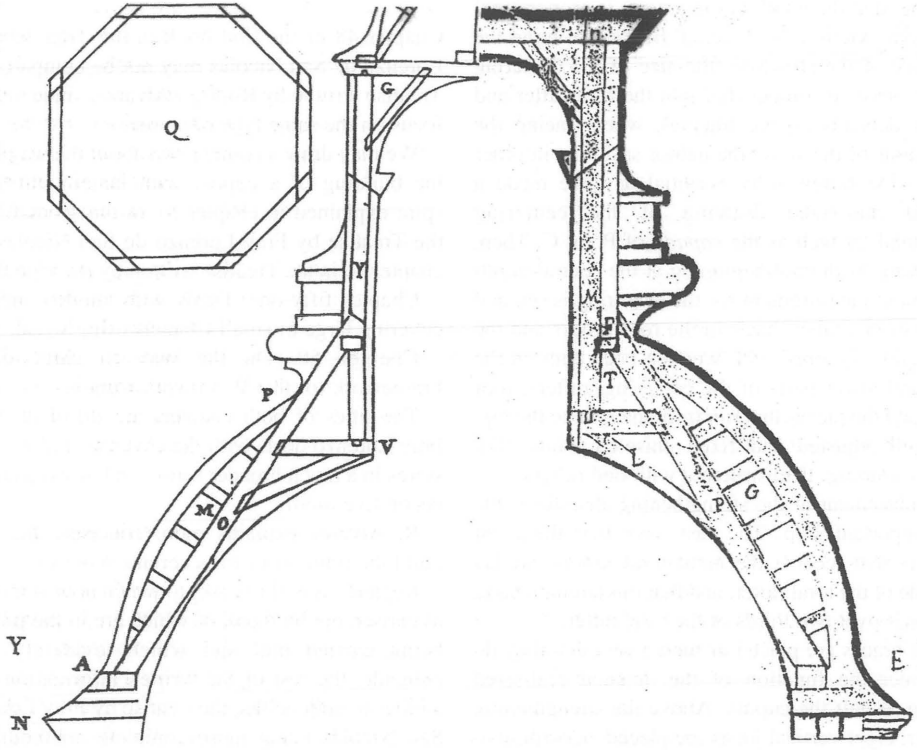


Figure 7
Comparison of the vertical section of the cupola framework with lantern by Fray Lorenzo de San Nicolas and that by Rodrigo Álvarez. Link among the strengthening chamfer, the chamfer where the rafters of the cupola framework are fixed through oblique cuts and the eight vertical supports of the lantern

cut, the strengthening chamfer and the eight vertical supports that make up the lantern, is different in both treatises. In this case, R. Álvarez represents such pieces and the way they are joined and in which they relate to each other more correctly.

None of the treatises explains where the eight vertical supports rest on the strengthening chamfer nor what is the relationship between these vertical supports and the upper chamfer where the rafters of the cupola are fixed through an oblique cut. This also affects the placement of the eight braces that do not hinder the function of the detailed real-sized drawing of half the cupola.

Conclusions

The spire used as decking and crowning element of a tower

Although there are several formal solutions to this type of spire, there is always a square or chamfered square, generally with a sharp pointed decking, which is finished in a cross, a weather vane or a ball, at the lower slope in the central portion.

The solution is defined by the proportionality of the width of the tower and the height. The higher the main support of the central portion of the spire, the more slenderness that is achieved, and the more resistance to the wind.

When building the spire, there are two framework mechanisms to counteract the strength of the wind.

— Abundance of wood. The weight is concentrated at the bottom of the main support and resistance of the main support itself.
The main support of the central portion, which is slightly higher and has a squared or chamfered plan, should rest at the bottom. The crossed ties form a square where the main support rests. By resting in the central areas of the void space, this member acts both as beam and tie, since the size of the tie should be out of proportion because it receives the weight of the whole support. On the other hand, the abundance of wood at the bottom of the structure also helps the building to counteract the strength of the wind.
The main support, which is composed of large vertical pieces, rests on the square formed in the inferior horizontal plan, where the spire is strengthened, as the treatise says. The way to carry out this joint is very important and it is not contained within the text.
Apart from the buttress on the wall, concentric buttresses in the inferior horizontal plan are needed.
— Less distance in relation to the main support acts as overhang against the wind.
Although the height of the main support is considerable, it can be less exposed to the horizontal force of the wind by shortening the distance of the overhang by using lower slopes that come from the concentric buttresses, including the external one, and underpin the vertical members that form the main support.

This model of spire is a very solid structure, and its appearance and construction is far away from the traditional manner in which the fine woodwork masters worked within the Spanish peninsula.

Since it is an imported model, in order to get to know its precedents and any written text concerning its construction, we should study same in its places of origin, both by seeing built samples of them and their description in any treatises that may exist on the subject.

During the reign of Phillip II, several models of spire were used in the renovations and new constructions carried out within the Royal Palaces. The golden tower of the Alcázar of Madrid, which was finished in 1569, was an imposing view in the skyline of the capital city and the use of this kind of structures was thus extended. Figure 8.

Spire of cupola framework with lantern.

The vocabulary used in *carpintería de armar* which is employed in both volumes by Fray Lorenzo when explaining how to build those structures is similar to that used by Rodrigo Álvarez in the second book, which includes chapter 25 up to chapter 50, where, apart from the Framework of this Woodwork Cupola, the author displays a whole construction system using wood which was preserved thanks to the oral transmission of the labor techniques. (The Spanish *carpintería de armar*).

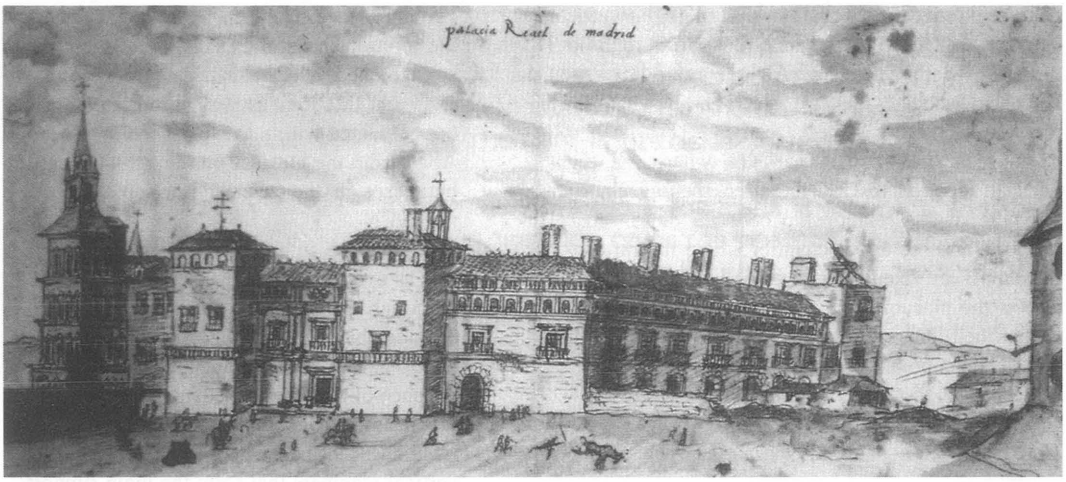


Figure 8
Main facade of the Alcázar with the new tower that culminates in a spire. A. Wyngaerde. National Library of Vienna

I would like to draw attention to the similarities and differences of the cupola framework with lantern with the wood construction system, which is peculiar of the Spanish *carpintería de armar.* In our case, the buttress is directly placed on the horizontal beam, whereas in earlier construction practices, a base was placed on the horizontal beam and on the base, the cant strip and the tie, subsequently fastening the buttress to the tie through indentations made halfway through the width of each piece. Figure 9.

In chapter 50 of the treatise by Fray Lorenzo we find the description of a chamfered structure with ties. The bases rest on the horizontal beams, and the ties are fastened to them through indentations made halfway through the width of each piece; to anchor the buttresses to the ties, it is explained how to place some short and thick pieces of timber on the base and on another horizontal beam that is as thick as the ties. This is then anchored at the angles where the base is and from these short pieces of timber or diagonal timbers, a metallic piece is placed, which fastens everything and thus constitutes a safe junction.

When no more ties can be placed in the framework, the buttresses are directly placed on the horizontal beams. A chamfered square is formed with the buttresses, which fits through indentations made with large *cogotes* nailed both on the upper and lower parts. On the junctions, iron squares are placed with the base of the chamfer and each branch at least two thirds long. It is then reinforced with masonry and carpentry work.

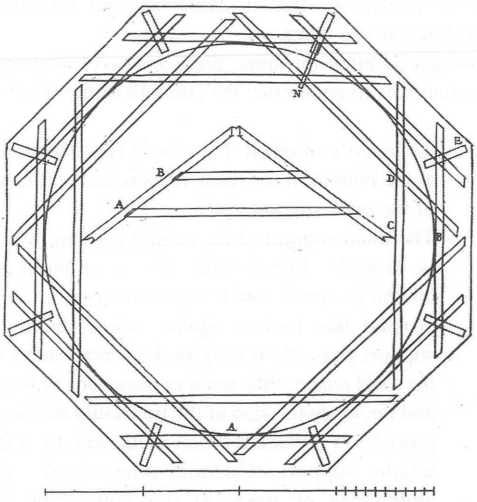


Figure 9
Chamfered structure with ties, as defined by Fray Lorenzo de San Nicolas

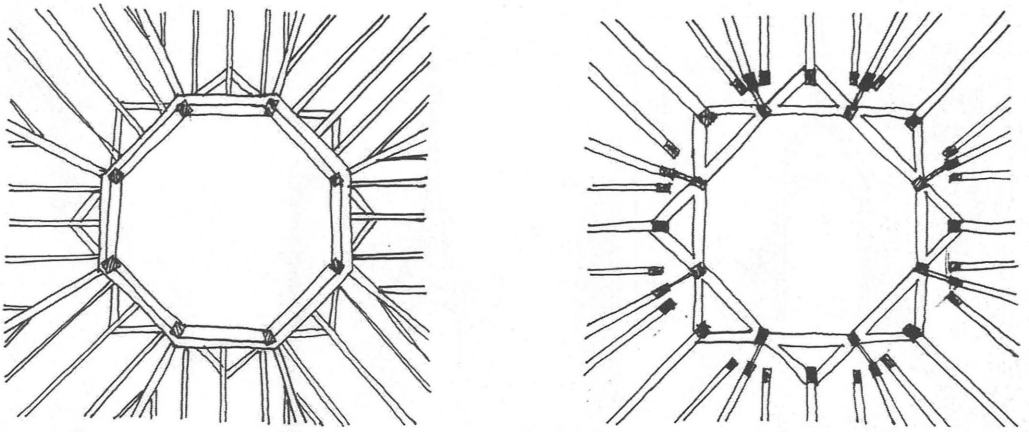


Figure 10
Horizontal sections over the strengthening chamfer and the chamfer where the rafters of the cupola framework are fixed through oblique cuts

Despite the strength required to carry out all these operations in the buttresses, the structure may not be achieved without the strengthening chamfer, which is built at a height equivalent to two thirds of the toral rafter (plain surface among horizontal beams in rafter and horizontal beam decking), similarly to the process pertaining to the placement of ties on the chamfered structure described in chapter 50 of the treatise by Fray Lorenzo. Figure 10.

The link among the upper chamfer where the rafters of the cupola are fixed through oblique cuts, the strengthening chamfer and the eight vertical supports that form the lantern, is described differently in both treatises.

None of the treatises explains where the eight vertical supports rest on the strengthening chamfer nor what the link is between such vertical supports and the upper chamfer where the rafters of the cupola are fixed through oblique cuts. This also influences the placement of the eight braces in order not to hinder the function of the detailed real-sized drawing of half the cupola.

It does not seem advisable to cut the vertical supports that form the lantern at the height of the upper chamfer where the rafters of the cupola are fixed through oblique cuts. At this height, it seems more reasonable to have some kind of joint among all the members.

All the treatises from the 17th century that have been studied have a similar approach, although there are some obvious differences.

Juan García Berruguilla, in *Tratado Quinto. En que se trata de varios modos de Armaduras*, [Fifth Treaty. On different Frameworks] shows an example of a spire of cupola framework with lantern, and 16 trusses, a solution that is in no way similar to the approach of the treaties dealt with in this paper. Figure 11.

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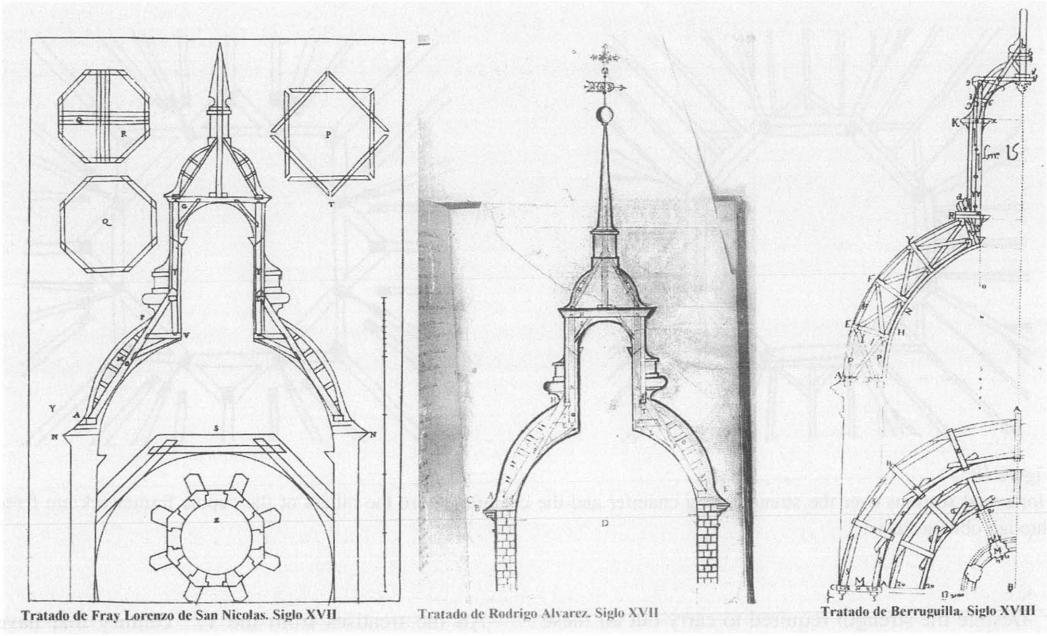


Figure 11
Cupola frameworks with lantern, as defined in the treatises by Fray Lorenzo de San Nicolas, Rodrigo Álvarez and Juan García Berruguilla

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Vault theory in Spain between XVIIIth and XIXth century: Monasterio's unpublished manuscript *Nueva teorica sobre el empuje de bovedas*

Santiago Huerta
Federico Foce

This paper intends to offer a first introduction to an unpublished manuscript recently found by one of the authors in the Library of the Escuela de Ingenieros de Caminos, Canales y Puertos of the Universidad Politécnica de Madrid and entitled *Nueva teórica sobre el empuje de bóvedas*.

In the opinion of Fernando Sáenz Ridruejo (1998; see also 1990), the author of this important manuscript is, most probably, Joaquín Monasterio, Civil Engineer of the first promotion of the «Old School» of Civil Engineers established in 1802 by Agustín de Betancourt. The information about this obscure, though brilliant, young professor is very scarce. Rumeu (1980) only cites his name and we are indebted to F. Sáenz for the following information: Promotion in 1804; in 1809 figures as professor in a proposal for the Academy of Sciences and in 1810 it was promoted to «Ingeniero de 1ª Clase». After this date there is no other mention in the files. Between 1805 and 1806 the Escuela de Caminos was closed and in Sáenz's opinion he could have written his *Teorica* in this time. This agrees pretty well with the internal evidence in the manuscript: among others, Monasterio cites Coulomb (1773) and Rondelet (first edition 1802) but does not cite Gauthey (first edition 1809), though the matter is not settled yet.

It is certain that the manuscript came to the hands of Eduardo Saavedra, one of the most prominent Spanish engineers of the 19th century. In the first numbered page of the manuscript we find, in fact, the following note by Saavedra: «Este trabajo es de un profesor de la primitiva Escuela de Caminos llamado Monasterio, y me lo regaló mi maestro D. Francisco de Travesedo».

The manuscript is cited by Saavedra himself in the Dictionary of Clairac (1877) (article «Bóveda»), as part of the Spanish bibliography on the subject. The manuscript belonged then to the private library of Saavedra, who gave it (unknown date) to the Library of the Escuela de Caminos.

The manuscript

The manuscript consists of an Introduction, three chapters devoted to the collapse analysis of non-symmetric and symmetric arches and a fourth chapter on the thickness of the abutments and their way of cracking. In the complex, ninety numbered pages clearly handwritten, with few corrections, and two Plates (Figures 1 and 2, here) with 25 figures.

By simply observing the two plates at the end of the text, it is not difficult to appreciate the general character of Monasterio's theoretical approach. For instance, we find there the illustration of the collapse modes of non-symmetric arches, a topic rarely investigated and probably never tackled before him. Moreover, we recognize the general research of the actual fracture of masonry abutments, an argument requiring new considerations about the stabilising contribution of the arch piers.

As we shall see, not everything of Monasterio's analysis is correct nor his deductive process is always

clearly stated. Anyway, the manuscript contains material enough to guarantee a higher theoretical quality in comparison with preceding and later studies, even the best ones usually celebrated by the official historiography on the subject.

The *Introducción*

The *Introducción* (3-11) to the *Nueva Teórica* is a beautiful manifest of scientific methodology. Monasterio is perfectly aware that the theory of the masonry arch has been treated «hasta el presente con . . . poca exactitud y extension». (3) He writes that some authors «solo se extienden à dar reglas practicas» giving nothing more than «una confusa mezcla de principios de Geometria y Estatica, mal intendidos y aplicados»; other authors have developed «calculos fundados en hipotesis falsas, o formulas inutiles, tanto por la arbitrariedad y restricciones . . . como por que solo sirven para impedir algunos movimientos, y no los que mas comunemente adquiren las bovedas». These last authors «creyeron que para asegurarse de la solidez de un arco, bastaba resolver dos cuestiones que se refieren à impedir separadamente los movimientos de traslacion y rotation».

Monasterio starts from these critical comments in order to establish a general theory of the masonry arch in accordance with the following method of investigation:

> Sabemos que un arco es el agregado de varios cuerpos, à quienes se dà el nombre de dovelas, capaces por su figura y colocacion de moverse de diferentes maneras, y al mismo tiempo que para reducir al estado de reposo un sistema de cuerpos ligados entre si y solicitados por varias fuerzas, es necesario tener tantas condiciones que satisfacer, cuantos movimientos diferentes se pueden concebir en èl: asi, pues, si la teorica de bovedas ha de tener por objecto impedir que los arcos se vengan abajo, y que padezean alteraciones susceptibles de perjudicar á su solidez, es claro que no las desempeñaremos devidamente, mientras no se averiguen primero todos los movimientos que pueden adquirir las diferentes partes en que se divide una boveda, para hallar despues con arreglo á este conocimiento las condiciones correspondientes á evitar cada uno de aquellos movimientos en particular: y solo siguindo el camino trazado por este raciocinio, conseguiremos que nuestras aplicaciones sean utiles á la practica, y esten exentas de los errores cometidos hasta aqui. (3-4)

Now, the movements of the voussoirs —considered as rigid blocks subject to friction and unilateral constraints— may be (absolute and relative) rotations around the joint edges and (absolute and relative) translations along the joint lines. As an arch can collapse «abriendose por uno, dos, tres o mas trozos, y ademas cada uno de estos adquirir el movimiento de rotacion o el de traslación», it is evident that

> segun sean diferentes las circunstancias que acompañen à estos movimientos, asi deberan variar de forma las condiciones que los evitan: de suerte que . . . el exacto conocimiento de todas estas circunstancias ha de depender necesariamente del numero de permutaciones que admiten dos letras que representan la una el movimiento de traslacion, y la otra el de rotación. (4)

By naming the (absolute and relative) translations with *t* and the (absolute and relative) rotations with *r*, Monasterio represents the collapse modes of a non-symmetric arch by means of permutations of the letters *t* and *r* in accordance with the following rule: for any permutation, the number of letters gives the number of voussoirs in which the arch breaks at collapse, the order (from left to right) gives the type of (absolute and relative) movement taken by the voussoirs.

From a strictly mathematical reasoning, these permutations are infinite and Monasterio writes them in the form *t*, *r*, *tt*, *tr*, *rt*, *rr*, *ttr*, *trt*, *rtt*, *trr*, *rtr*, *rrt*, *rrr*, *ttt*, *tttr*, *ttrt*, *trtt*, *rttt*, etc. From a mechanical point of view, however, some of them are kinematically impossible. For instance, Monasterio observes that the permutations *t*, *r*, and *rr*

> no pueden tener cabida . . . por que atendida la figura de cuña de las dovelas, su impenetrabilidad y la convexidad del intrados mirado desde arriba para abajo, ni un trozo puede adquirir aisladamente el movimiento de traslacion, ni menos dos solos el movimiento de rotación. (5)

Moreover, he adds that the permutations with more that three letters can be decomposed, without changing the order, into groups formed by the following eleven permutations *tt*, *tr*, *rt*, *ttr*, *trt*, *rtt*, *trr*, *rtr*, *rrt*, *rrr*, *ttt*. For instance, he says that the permutation *trrtr* is not relevant as it is formed by the permutations *trr* e *tr* which already represent two collapse modes. Finally, he concludes that these

eleven permutations can be further reduced to seven by observing that in the four permutations *ttr*, *rtt*, *rtr*, *ttt* the first two letters already represent a possible collapse mode, so that «todos los diferentes movimientos con que un arco puede venirse abajo» can be given by the seven permutations *tt*, *rrr*, *rrt*, *trr*, *tr*, *rt*, *trt*.

The sequence of these permutations reflects the organisation of chapters 1-3. The first one —*tt*— corresponds to the collapse by translation of two voussoirs (Plate 1, Gig. 1); the second one —*rrr*— corresponds to the collapse by rotation of three voussoirs (Plate 1, Fig. 2); the last five —*rrt*, *trr*, *tr*, *rt*, *trt*— correspond to collapse modes involving both translation and rotation of two or three voussoirs (Plate 1, Figs. 3-7). In particular, the permutations *tr* and *rt* imply a composed relative movement of translation and rotation between two voussoirs (Plate 1, Figs. 5-6).

In a few pages it should be impossible to go deeply into the questions discussed by Monasterio in the four dense chapters of the manuscript. We must, then, limit ourselves to present the main features and results of his study. It is of help in these sense the uniform process of reasoning followed throughout the text. Starting with the collapse analysis of non-symmetric arches, Monasterio firstly deduces the general conditions of equilibrium to be fulfilled in order to prevent the seven modes of failure previously mentioned; then he specializes the general conditions to the case of symmetric arches and applies them to vaults and domes with simple geometry, so that he

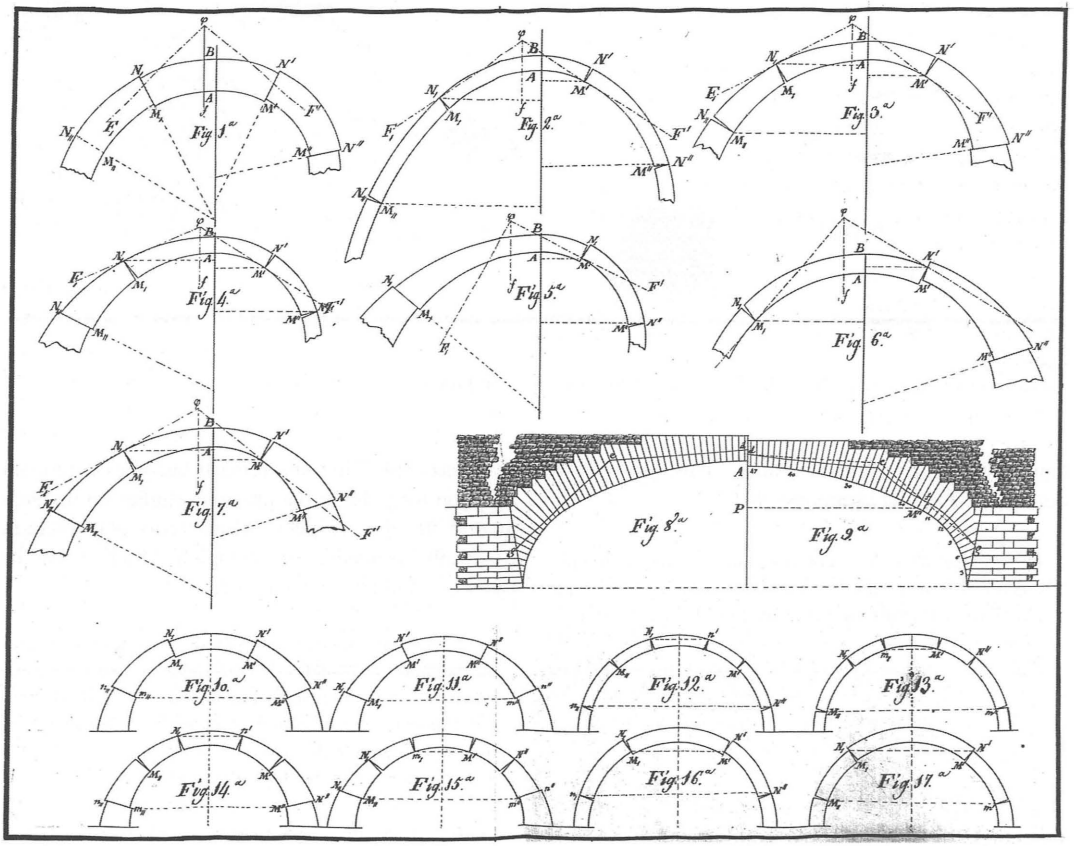


Figure 1
Monasterio's Plate 1, with the collapse analysis of arches

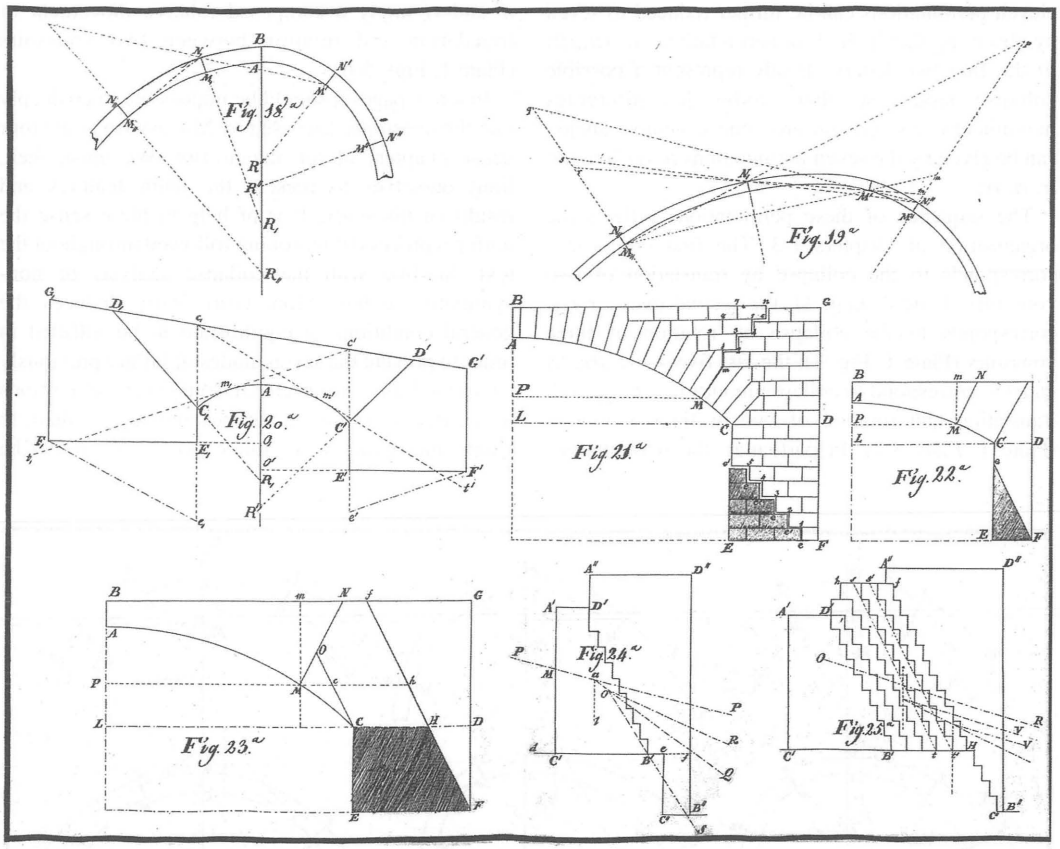


Figure 2
Monasterio's Plate 2, with the collapse analysis of the system «arch'buttress»

can obtain quantitative results. This process is developed with the awareness that,

> pudiendose abrir los arcos por tantas partes diferentes, cuantas son sus juntas de hecho, para estar seguros de que aquellas condiciones se verifican en toda la extension de la boveda, debemos referirnos á aquella posicion de trozos mas poderosa para hacerlos volcar, pues claro està que si el movimiento no se verifica considerados los trozos mas dispuestos a moverse, menos se verificarà con cualesquiera otros (8-9)

This means that the search for the collapse condition must be carried out «por medio de la doctrina de maximos y minimos, y no valiendose, como se ha hecho comunemente, de observaciones practicas». (9) This last remark becomes a rational criterion for judging the previous studies on the arch theory. In this respect, Monasterio ackwoledges Coulomb's primacy, even though he observes that his analysis would have been correct

> si . . . no hubiera confundido en una sola las dos fuerzas horizontales dimanadas de considerar un trozo, ya como potencia, ya como resistencia: suposiciones que hacen se diferencien entre si aquella fuerzas, constantemente en los movimientos de rotacion, y en los de traslacion cuando se introduce el rozamiento. (9)

The previous quotation reflects a deep understanding of the mechanical questions and probably constitutes an anticipation of Persy's

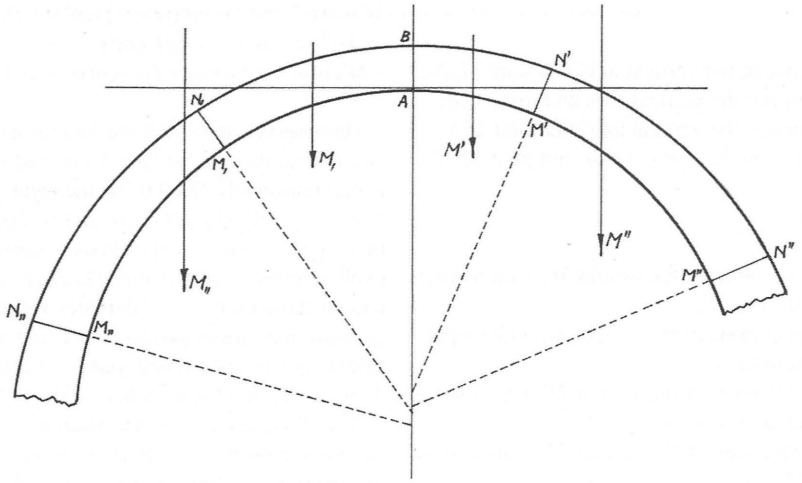


Figure 3
Monasterio's general scheme of a non-symmetric arch

criticism towards Coulomb's application of the method of maxima and minima. With similar rigour Monasterio specifies the hypotheses of his theoretical analysis: he explains that the cohesion can be neglected «por ser insensible o casi nula cuando el mortero se halla blando, esto es, recien construidos los arcos: tiempo, al cual deben referirse nuestras formulas, por ser la epoca en que aquellos corren mas riesgo de arruinarse» (10); on the contrary, he affirms the necessity of taking into account the role of friction, «por que el objecto de dar à las bovedas un estado mas firme y permanente que el de l'equilibrio, no puede conseguirse . . . si no se admite une fuerza pasiva, cual el rozamiento, que obrando solo como resistencia sofoque el movimiento que intentan producir las activas»; finally, he observes that, even if the materials have limited compressive strength, «podemos muy bien desentendernos de calcular si las dovelas, pilares y demas partes del arco tienen la suficiente robustez para aguantar sin desmoronarse à la presiones que sufren, seguros de que la tendran, mientras sus dimensiones, por pequeñas que parezcan con relacion à este objecto, guarden las proporciones que exigen las demas consideraciones que llevamos mencionadas». (10-11). As it is easy to understand, this last point focuses a fundamental of the modern limit analysis of the arch as it affirms that global stability, and not local strength, is the main question of masonry structures.

The first chapter

As anticipated, this first chapter, «De las condiciones necesarias para evitar los movimentos puros de traslación» (12-33), deals with the collapse of the arch by translation of the voussoirs. Monasterio initially studies a non-symmetric arch and analyzes the collapse mode of Plate 1, Fig. 1, representing the permutation *tt*. The procedure to establish the stability condition is based on the fact that, at collapse, the direction of the forces at the rupture joints are known.

Before developing Monasterio's analysis, we give here his notations with reference to Figure 3

Coordinates (with respect to the vertical and horizontal axes)

$M_{,,}=(y_{,,};x_{,,})$ $M_{,}=(y_{,};x_{,})$ $M'=(y';x')$ $M''=(y'';x'')$
$N_{,,}=(u_{,,};z_{,,})$ $N_{,}=(u_{,};z_{,})$ $N'=(u';z')$ $N''=(u'';z'')$

Weights

$M_{,,}$ = weight of the voussoir $AM_{,,}N_{,,}B$
$M_{,}$ = weight of the voussoir $AM_{,}N_{,}B$
M'' = weight of the voussoir $AM''N''B$
M' = weight of the voussoir $AM'N'B$

Angles

$\alpha_{,,}$ = angle between the vertical axis and joint $M_{,,}N_{,,}$
$\alpha_{,}$ = angle between the vertical axis and joint $M_{,}N_{,}$
α' = angle between the vertical axis and joint $M'N'$
α'' = angle between the vertical axis and joint $M''N''$

Lever arms

$X_{,,}$ and $Z_{,,}$ = lever arms of the weight $M_{,,}$ with respect to the points $M_{,,}$ and $N_{,,}$
$X_{,}$ and $Z_{,}$ = lever arms of the weight M, with respect to the points M, and N,
X' and Z' = lever arms of the weight M' with respect to the points M' and N'
X'' and Z'' = lever arms of the weight M'' with respect to the points M'' and N''

Moreover, $k = AB$ is the thickness of the arch at the crown joint and f is the friction angle.

Summarizing Monasterio's reasoning, the following steps can then be developed:

1) Decompose the weight (M,+M′) in two forces F' and F' which form the angles λ, and λ' with the vertical and are equal to the complements of the friction angle f at the joints M,N, and $M'N'$, respectively;
2) Impose the equilibrium of the weight ($M''-M'$) and the force F' with respect to the outwards translation along the joint $M''N''$.

By conserving the original numbering of the manuscript, the stability condition is then given by the following disequality

$$'M'' - b'M' - c'M, \geq 0 \qquad (A)$$

where the coefficients a', b' and c' satisfy the relationships

$$a' = \cos(\alpha''-f)\ \mathrm{sen}(\alpha' + f + \alpha, + f)$$

$$b' = \cos(\alpha'+f)\ \mathrm{sen}(\alpha'' + \alpha,) = a' + c'$$

$$c' = \cos(\alpha''+f)\ \mathrm{sen}(\alpha' - f - a, - f)$$

Monasterio treats this disequality in order to simplify its discussion and obtain, after some passages, the new form

$$M''\cot(\alpha''-f) - M'\cot(\alpha'+f)\}\mathrm{sen}(\alpha'+f)/ \mathrm{sen}(\alpha''-f-\alpha'+f) + \{M''\cot(\alpha''-f) - - M'\cot(a'+f)\}\mathrm{sen}(a,+f)/\ \mathrm{sen}(\alpha'' + \alpha,) \geq 0 \qquad (7)$$

He observes, then, that the first term depends on α' and α'' and the second term on α, and α''. Moreover, if one reasonably fixes α'' at the right springing, the two terms only depend on α' and α, , respectively. In this case «sus respectivos minimos podran explicitamente hallarse, ó por la diferenciacion, ó por tanteos dando à α' y α, diferentes valores: si la suma de estos minimos es positiva . . . concluiremos de este calculo que el movimiento puro de traslacion no tiene de modo alguno lugar en la boveda». (21)

The disequality (7) is the starting point of various developments. First of all Monasterio studies the case of absence of friction and finds the equilibrium equation

$$M = A\ \mathrm{tang}\alpha \qquad (10)$$

where A is a constant and M is the weight of a generic voussoir subtended by angle α. This equation «se halla bajo diferentes formas en casi todas las obras que tratan del empuje de bovedas, y parece que el objeto principal de sus autores no ha sido otro que de darla a conocer como si en ella solo estribara todo el fundamento de la teorica, siendo asi que es la mas inútil». (11) Anyway, Monasterio uses equation (10) in the case of a vault and a dome of constant infinitesimal thickness. As expected he finds the analytical equation of the «catenaria plana o de cañon seguido» in the first case and the equation of the «catenaria de revolucion o de media naranja» in the second one.

Another use of the disequality (7) is given by Monasterio to treat symmetric arches. In this case he finds that the stability condition with respect to the collapse by translation becomes

$$M''\ \cot(\alpha''-f) - M'\cot(\alpha'+f) \geq 0 \qquad (B)$$

«donde se vé que la boveda satisfara en todas sus juntas à esta condicion, si el minimo de $M''\cot(\alpha''-f)$ es mayor que el maximo de $M'\cot(\alpha'+f)$». (28) This conclusion perfectly agrees with Coulomb's stability condition stated by the method of maxima and minima. The two terms of (B) are nothing else than the values of the horizontal thrust satisfying the equilibrium with respect to the outwards translation

along the joint α'' and the inwards translation along the joint α'. As Monasterio correctly affirms generalizing Coulomb's statement, the disequality (B) can be useful to study the two opposite collapse mode in Plate 1, Figs. 10 and 11, depending on the relative position of the rupture joints.

An application of disequality (B) is given by Monasterio for determining the minimum friction coefficient preventing the collapse of a semi-circular arch of constant thickness. He obtains that the collapse by translation becomes impossible for tang$f > 0{,}31$. This value, corresponding to $f = 17°$, is quantitatively correct as we know (Sinopoli et al., 1997) that the collapse of Fig. 10 can occur when tangf = 0,305, with rupture joints for $\alpha' = 29°$ and $\alpha'' = 90°$.

THE SECOND CHAPTER

In this second chapter, «De las condiciones que impiden los movimientos puros de rotación» (33-49), Monasterio deals with the collapse by rotation, starting from the general case of non-symmetric arches. He refers to Fig. 2 of Plate 1, corresponding to the permutation *rrr*, and observes that at collapse four conditions can be stated:

1) the component F' of the weight $(M,+M')$ must go through the intrados edge M';
2) the component F, of the weight $(M,+M')$ must go through the extrados edge N, ;
3) the moment of F, with respect to the intrados edge $M,,$ must be smallest than the moment of the weight $(M,, - M,)$ with respect to the same point;
4) the moment of F' with respect to the extrados edge N'' must be greater than the moment of the weight $(M'' - M')$ with respect to the same point.

By analytically treating these conditions Monasterio finds the following stability disequality

$$a''M''Z'' - b''M'X' + c''M,Z, - d''M,,X,, \geq 0 \qquad (C)$$

where the coefficients a'', b'', c'' and d'' satisfy some relationships among the coordinates of the centers of absolute and relative rotation.

Disequality (C) is specialised by Monasterio for some important cases. The first one concerns vaults and domes of infinitesimal thickness. Once again he finds the equations deduced in the preceding chapter, «lo que nos prueba que las catenarias plana y de revolucion son las unicas curbas que deben formar las bovedas de cañon seguido y media naranja para que no se vengan abajo en el caso de der su espesor infinitamente pequeño». (40-41)

Monasterio deals then with the case of symmetric arches and specialises the disequality (C) for the two opposite collapse modes of Plate 1, Figs. 12 and 13. In particular, he develops the calculation for the cases in which a rupture joint opens at the crown, with hinge at the crown extrados or at the crown intrados. The corresponding stability conditions are then

$$M''Z''/(z''+k) - M'X'/(x'+k) \geq 0 \qquad (F)$$

$$M,Z,/z, - M,,X,,/x,, \geq 0 \qquad (G)$$

These disequalities are equivalent to the stability conditions which can be derived by a «proper» application of Coulomb's method of maxima and minima, as the two terms in (F) represent the values of thrust satisfying the rotational equilibrium around the extrados edge and the intrados edge when the thrust is applied at the crown extrados, and the two terms in (G) represent the values of thrust satisfying the rotational equilibrium around the intrados edge and the extrados edge when the thrust is applied at the crown intrados. We underline «proper» application because, as Coulomb's analysis of the rotational collapse mechanisms is fundamentally wrong and an explicit correction of his erroneous conclusions was given only in 1825 by Persy (Foce 2002; see also Foce, Aita in these Proceedings). From this point of view, Monasterio's analysis anticipates the correct application of the method of maxima and minima under the different form given in (F) and (G).

Besides the theoretical analysis, Monasterio applies the disequality (F) for determining the minimum thickness of a semi-circular arch, a case already studied in 1730 by Couplet under the a priori hypothesis that the rupture joints was at 45° from the crown. Couplet had found that the minimum thickness is $k = 0{,}1061x$, where x is the intrados radius. On the contrary, Monasterio finds by trial and error that the minimum thickness is between 1/8 = 0,125 and 1/9 = 0,111 of the intrados radius, and the rupture joint at the haunches is between 54° and 56° from the crown. This result is

quantitatively correct and agrees with the calculation by Petit (1835), who has given a better approximation of the minimum thickness with the value 0,114 of the intrados radius. In 1907 Milankovitch has obtained the rigourous value 0,1136 corresponding to the rupture joint at 54°29' from the crown.

As concerns the collapse by rotation, Monasterio does not limit the analysis to the mode previously investigated for the semi-circular arch. He observes that also the opposite collapse mode corresponding to the disequality (G) must be considered, in particular for the domes. He applies then the disequality (G) to a semi-circular dome and finds that the minimum thickness is between 1/23 = 0,043 and 1/24 = 0,041 of the intrados radius. On the basis of this result, Monasterio rightly critizes Rondelet and the «formula suya», according to which a semi-circular dome of nil thickness would be equilibrated.

The third chapter

This third chapter, «De las condiciones necesarias para que no se verifiquen los cinco movimientos mixtos, y reduccion de todas las generales à otras mas sencillas» (50-66), begins with the analysis of the five collapse modes of a non-symmetric arch involving both translation and rotation and corresponding to the permutations *rrt*, *trr*, *tr*, *rt*, *trt*. As in the two preceding chapters, Monasterio determines the stability condition by imposing known requirements about the action of the internal forces at the rupture joints for each mode of collapse.

Without entering into details, we limit ourselves to give the stability conditions whose fulfilment prevents the collapse modes mentioned above. As concerns the «movimento mixto de primera especie», that is the permutation *rrt* (Plate 1, Fig. 3), Monasterio finds the stability conditions

$$a'''M''Z'' - b'''M'X' + c'''M,Z, - d''M,,X,, \geq 0 \qquad \text{(H)}$$

where the coefficients a''', b''' and c''' are known satisfy known relationships among the coordinates of the centers of rotation and the friction angle.

For the «movimento mixto de segunda especie», that is the permutation *trr* (Plate 1, Fig. 4), the condition becomes

$$a'^{\sim}M''Z'' - b'^{\sim}M'X' + c'^{\sim}M,Z, - d'^{\sim}M,,X,, \geq 0 \qquad \text{(I)}$$

where again the coefficients are satisfy known relationships among the coordinates of the centers of rotation and the friction angle.

In the case of a symmetric arch, the two types of collapse are represented in Plate 1, Figs. 14 and 15. In particular, when the collapse occurs with a rupture joint at the crown the stability conditions take the simple form

$$M''\cot(\alpha'' - f) - M'X'/(x' + k) \geq 0 \qquad \text{(M)}$$

$$M,Z,/z, - M,,\cot(\alpha'' + f) \geq 0 \qquad \text{(N)}$$

These last disequalities can be easily interpreted in terms of Coulomb's method of maxima and minima.

Coming back to the non-symmetric arch, Monasterio gives also the stability conditions for the others three collapse modes. Without reporting these conditions for the sake of brevity, we only add that an important remark about the collapse modes of fourth and fifth kind, represented in Plate 1, Figs. 5-6 for the non-symmetric arch and Figs. 16-17 for the symmetric arch (these latter are La Hire's mode and its opposite). In fact, the mechanical analysis of these two kinds of collapse modes does not seem to be correct. The mixed movements of fourth and fifth kind show that a composed movement of translation and rotation takes place at the rupture joint $M'N'$. Following Monasterio's reasoning on Fig. 5, for instance, the force F' is contemporaneously required to go through the intrados point M' and to form the friction angle with the normal at the joint. If we interpret this situation in terms of thrust line, we must conclude that the thrust line necessarily goes outside the arch ring under the joint $M'N'$, that is the arch cannot be stable. As any joint can be a rupture joint, the only possibility to remove this contradiction is that the tangent to the intrados curve at the generic point M' coincides with the boundary of the friction cone at the joint $M'N'$. Unfortunately, Monasterio does not realize this contradiction, which holds also for the collapse mode of Fig. 6, so that his discussion of the movements of fourth and fifth kind is substancially wrong.

After Monasterio, this same type of mistake has been made by some post-Coulombian authors, for instance Poncelet (1835). The first author who has clearly described the eight collapse modes of a symmetric arch seems to be Michon in his beautiful

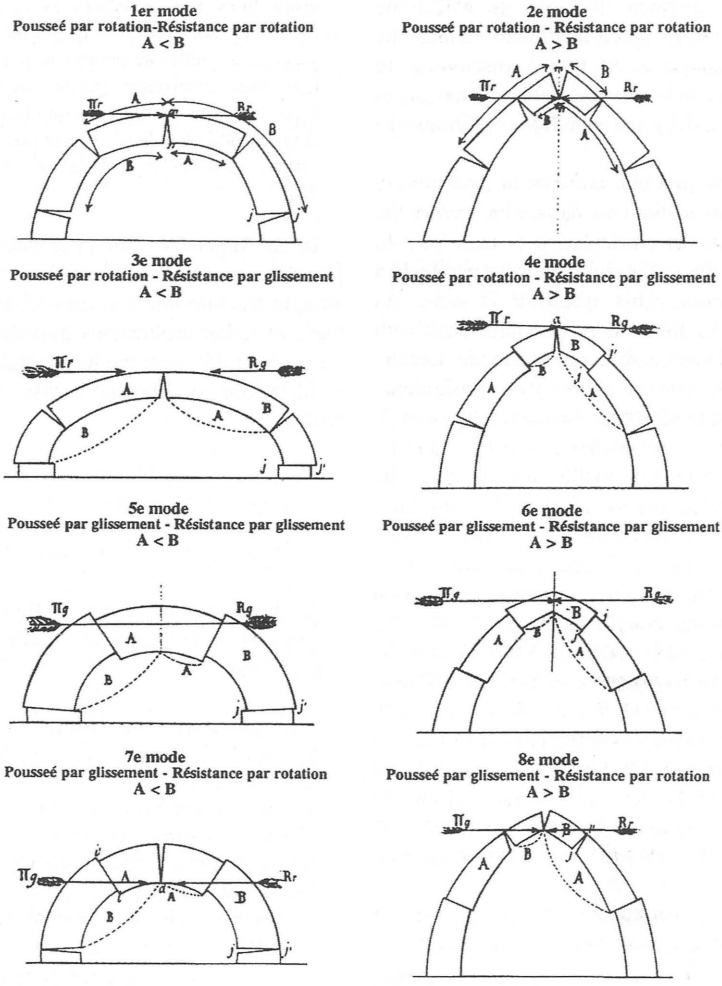


Figure 4
The eight collapse modes of a symmetric arch (redrawn from Michon, 1857)

Instruction of 1857 (Foce 2002). Michon's mechanisms are collected in Figure 4 and can be compared with the eight collapse modes given by Monasterio, provided that for these latter we consider a rupture joint at the crown.

The comparison shows that La Hire's collapse mode and its opposite are excluded from Michon's scheme and substituted by his seventh and fourth mode, respectively. Despite the correctness of Michon's analysis, Saavedra (1860) has repeated Monasterio and Poncelet's mistake in his Spanish translation of Michon's *Instruction* of 1857. This paradoxical circumstance is an evidence of the difficulty of the matter and may serve as a justification of Monasterio's erroneous discussion.

THE FOURTH CHAPTER

The last fourth chapter, «Aplicacion de la doctrina expuesta en los capitulos anteriores à la determinacion del grueso de machones» (67-90), deals with the

thickness of the abutment in order to avoid the collapse of the system «arch-abutment». Since the beginning, Monasterio restricts the discussion to symmetric systems and limits the collapse analysis to the modes described by the stability conditions (F) and (M).

The point of the problem consists in determining the correct weights of the two parts which enter the stability conditions. In particular, it is necessary to know the fracture lines of arch fill and abutment when the collapse occurs. This question is new. As Monasterio remarks, the authors who have dealt with the matter have always considered «cada pie derecho formado de un solo trozo de piedra, y de consiguiente capaz de oponer al tiempo de volcarse una resistencia mayor de la que tiene realmente». (67) On the contrary, Monasterio reasonably admits that the abutments and the fill must break along fracture lines whose inclination depend on the relative sizes (length and height) of the masonry blocks (see Plate 2, Fig. 21). For instance, if the collapse occurs by rotation and then the stability condition (F) must hold, the weight M' is measured by the area AMNBA and the weight M'' is given by the area of the semi-system, less the triangular surface *EeF* (see Plate 2, Fig. 22). If the same type of masonry blocks is used for fill and abutment, the angles *mMN* and *EeF* are equal and their tangent is half the ratio length/height. In particular, for the sake of safety Monasterio considers square block and finds that the angles *mMN* and *EeF* measure 26°34'.

On this theoretical basis, Monasterio develops a very sophisticated analysis which is impossible to report here. We limit ourselves to add that, after Monasterio's unknown contribution, the problem of the fracture of the abutment was independently considered by other authors with less rigour. Dealing with the stability of the system 'arch-abutment', Gauthey remarks that

> l'analyse précédente suppose nécessairement que les différentes portions de la voûte forment des masses solides dont toutes les parties sont parfaitement liées entre elles, et ne peuvent éprouver aucun tassement. Elle suppose également que les culées sont établies sur une base entièrement incompressible, et que, dans la chûte de la voûte, ces culées tourneraient, sans se disjoindre, autour de leur arrête extérieure. Ces suppositions sont, en général bien éloignées de la verité. La chûte d'un pont ne pourrait guere arriver sans qu'il ne se fît quelques disjonctions dans ses culées, avec quelque soin qu'elles eussent été construites; et quand même il ne s'en fairait aucune, les culées ne pourraient point tourner autour de leur arête extérieure, où les pierres s'écraiseraient nécessairement sous l'effort qu'elles auraient á soutenir, et qu'on doit chercher par cette raison à repartir sur une surface suffisament considérable (Gauthey 1809, 324-325)

In an Appendix «Sur la résistance des murs aux pousées» to Gauthey's treatise, Navier assumes a straight fracture line and tries to demonstrate, on the basis of rather arbitrarious hypotheses, that it forms an angle of 45° with the horizontal. He also quotes a result given by Mayniel (1808, 98), according to which

> Un mur de 20 pieds de hauteur, dont on avait laissé consolider la maçonnerie, s'est rompu au niveau du sol, en formant une ligne de rupture qui eût pu dans le profil être la diagonale d'un carré qui eût l'épaisseur du mur.

In the *nouvelle* edition of Bélidor's *Sciénce des ingénieurs* of 1813, Navier confirms this idea when affirms that

> si le piedroit AE vient à tourner sur l'arête D, il ne sera pas soulevé en entier, à moins que son épaisseur ne soit très-peu considérable et que les pierres ne fassent *parpaini,* ou que l'adhésion des mortiers ne suffisament grande. Ce piédroit tendra à se partager suivant le plan DT, incliné de la moitié d'un angle droit, en sorte que la partie ADT ne sera point soulevée. Donc, on ne doit point en tenir en compte dans l'évaluation de la force du pédroit . . . (186)

The argument is taken again by Navier in his *Leçons* of 1826 and 1839 and in the later editions of Gauthey's *Traité des ponts*. Gauthey's observations have been accepted by Haupt (1851) and Cain (1879).

It is interesting to remark that Navier treats the buttress as a continuum and applies ideas from the soil mechanics. Monasterio, on the contrary, considers the buttress as an assemblage of rigid blocks. Vicat's experiences of 1832, Figure 5, seem to confirm Monasterio's result, even though Navier consider them as a confirmation of his theory. Attention to the influence that the size of the blocks have on the fracture line is given, unexpectedly, also by Walther (1854), Figure 6.

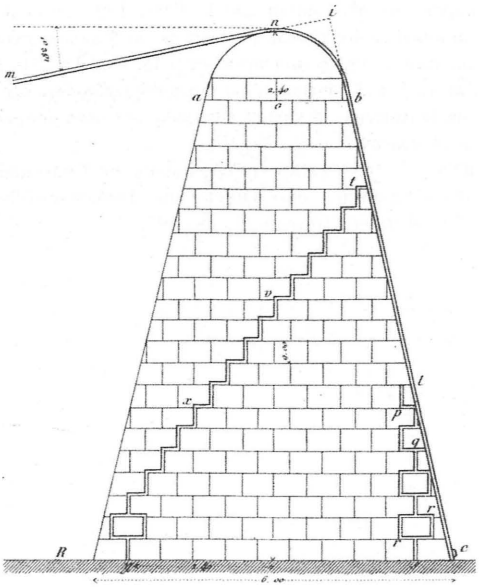


Figure 5

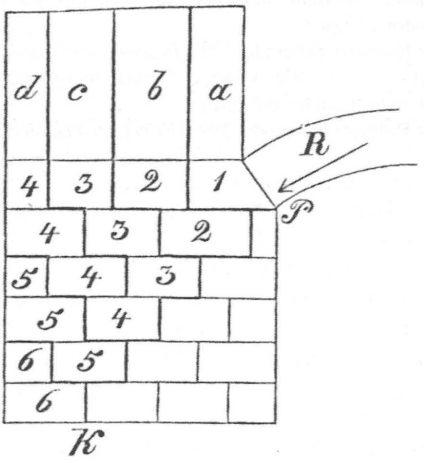


Figure 6

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Prestressed concrete: First developments in Italy

Tullia Iori

In February of 1939, at the height of the autarchy campaign in Italy, Gustavo Colonnetti, wrote from the pages of the journal *Il Cemento Armato*, attempting to persuade Italian engineers, scientists and politicians that «iron conservation must not be sought in absurd returns to decidedly outdated building technologies— nor in the adoption of no less absurd surrogates— but rather by proceeding, unperturbed, using all means available and the aid of science and experience, with the development of more advanced technologies» (Colonnetti 1939a, 22).

The words of the most famous —and troublesome— Italian scientist in the construction field amounted to a censure of the reactionary impositions of the regime, which favoured a return to traditional bearing walls and the autarchic vaulted ceilings. Analogous criticism was at the same time directed to parallel visionary experiments which aimed to substitute the iron reinforcing in concrete with wood or bamboo rods, irresponsibly disregarding the very low elastic modulus of these surrogates. These experiments were encouraged by the concrete industry, in search of rapid solutions in the face of the crisis determined by laws against the use of reinforced concrete in civil construction (Iori 2001).

The more advanced technology to which Colonnetti referred had already been under development for the last several years in Europe —the work of Eugène Freyssinet in France, and of Wayss & Freytag and Dywidag in Germany: the so-called «prestressed concrete».

Why was Colonnetti so enamoured with prestressing, to the point that he considered it to be the solution to the economic problems of the building sector?

There were at least two reasons.

The first is that the Italian scientist, respectively in agreement with Freyssinet, Eduardo Torroja and Ove Arup, had always considered reinforced concrete an "absurd", "strange" and "difficult" material. The two elements of which it is composed have almost opposite structural qualities, and the strength of their union lies precisely in this complete difference: one absorbs the stresses which the other is unable to withstand. But the paradox consists in the fact that the static reliability of reinforced concrete is based on a guaranteed adherence between the iron and the concrete, while adherence is actually heavily compromised by the inability of concrete to withstand tensile stresses and thus to match the deformation of iron. The inevitable cracks in the concrete in areas under tension had already raised doubts at the beginning of the century, during the pioneering stage of experimentation with reinforced concrete. Nor did the diffusion, towards the end of the 1930s, of special high-strength concretes provide a solution to the problem, because the performance of these concretes improved only in terms of compressive strength, while tensile strength did not increase significantly. Even the possibility of using high-strength steels, which would permit considerable material savings, was questioned, because of the low tensile strength of concretes and its tendency to crack as soon as it is subjected to expansion over a certain limit. Yet it appeared clear to Colonnetti —just as it did to his European colleagues— that with the technique of prestressing, the reciprocal relationship between

concrete and iron would be completely turned around: the reinforcement would no longer serve to withstand a given part of the stresses due to external loads, but rather to create in the concrete itself a preventative state of tension, opposite to that resulting from the external forces. The collaboration between the two materials is transformed into "coaction": the steel precompresses the concrete, which is then able to withstand tensile stresses due to the mechanism of the sum of the effects. This separation of roles solved the paradox of cracking in tension zones and immediately revalidated the use of both high-strength steels, which would be subject to extremely high tensile stresses, and of special concretes, required to withstand only compressive stresses. In concrete which is prestressed by means of pretensioning, both concrete and steel are stressed in conformance to their particular strength characteristics, thereby greatly increasing efficiency: the technique thus resulted in a considerable economy of materials.

The second reason for which Colonnetti pushed in favour of prestressing is that the new technique might finally begin to heal an open wound in the side of the building science community.

Colonnetti's clearly stated his opinion on the value of the theory of reinforced concrete formulated by Edmond Coignet and Napoléon de Tédesco more than forty years earlier, in 1894, and still used in 1939. He quite simply regarded the design methods as «lacking, absolutely lacking any scientific foundation, not only in the sense that, based as they are on unjustified and unjustifiable hypotheses, they arrive at conclusions which experience notoriously contradicts, but also in the sense that as the hypotheses themselves are incompatible and contradictory, one cannot even concede to the resulting theory the quality of a logical construction, capable of withstanding the most elementary criticism» (Colonnetti 1938, 61).

Those who had introduced these calculation methods into the building codes and to general use had not been misinformed about their validity; only later had the process assumed a permanent status, authorising the blind application of the simple and well-known methods of the elastic theory.

Colonnetti was a gifted theoretician. From 1917, as a young university professor at Pisa, he had studied the definition of equilibrium of a body in the presence of non-compatible deformations —a state of residual stress which he defined as a state of "coaction"; in 1924 he had formulated a theorem of minimum deformation energy which still carries his name: a generalisation of the theorem of Menabrea in the presence of elastic residual stresses. From 1937, he reorganised the corpus of the mathematical theory of the elastic solid, adapting it to a solid which is not perfectly elastic, but rather elasto-plastic, a hypothesis which is closer to the behaviour of reinforced concrete.

Without going into detail about his intuitions, by 1939 Colonnetti fully understood that states of artificial residual stress can improve the static performance of structures, and in parallel, that the "classic" design methods for reinforced concrete were in urgent need of substitution by rigorous scientific theory.

The technology of prestressed concrete gave him, on the one hand, a chance to promote the elimination of arbitrary design methods, and on the other, recognition and direct application of the precious studies of his youth.

In September of 1939, Colonnetti completed and published a design method for beams with pretensioned tendons, direct application of his elegant theory of "elastic coaction" (Colonnetti 1939b). In this new configuration, the hypotheses of the elastic theory could be scientifically applied: the compressive action of the steel on the concrete in fact throws the neutral axis to the exterior of the concrete section, which thus becomes entirely reactive, entirely compressed, and homogeneous, as it is no longer the reinforcing which must resist to external loads. The behaviour of the material can thus be described perfectly without resorting to unlikely procedures of homogenisation by bonding the steel to the concrete, or to the use of coefficients whose validity was not only false but lacking any physical significance.

Examples of prestressing thus far

Apart from his internationally recognised theoretical contributions, Colonnetti did not have an instrumental role in the pioneering phases of the development of prestressing. The leading figures were French and German engineers —as had been the case many years earlier with ordinary reinforced concrete.

In fact, prestressing had already been used for several different applications.

To cite a few examples in the specific field of construction, the technique of tamping the joints in stone arch bridges was widely used. It consisted in forcing mortar into the joints at the haunches, comparable to forcing a wedge between the stones, creating reactions which are normal to the foundation and thus shifting the pressure curve. In another example, the Howe truss, Figure 1, the vertical members, consisting of threaded iron tie-rods, were post-tensioned by tightening nuts at the ends, so as to induce sufficient compression in the two systems of sloping timber members as to cancel out any tensile stresses resulting from dead or live loads (Guidi 1928, 190).

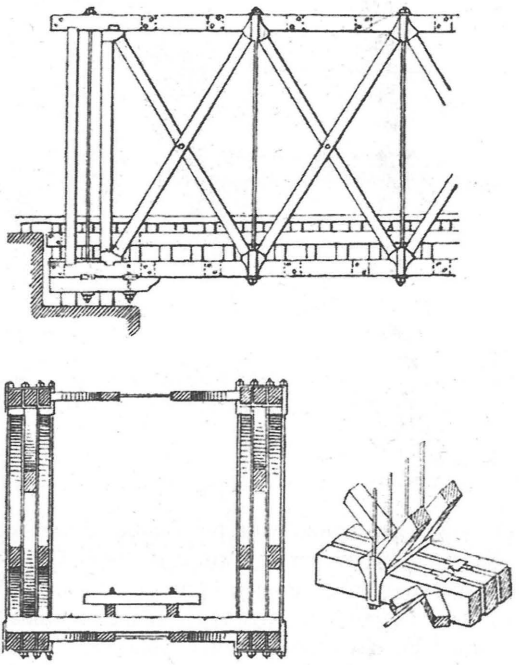


Figure 1
Howe truss: the vertical elements are threaded iron tie-rods, put under tension by tightening nuts at each end (Guidi 1928)

Around the mid-nineteenth century, a type of reinforced cast iron beam with pre-stressed reinforcing was in use. The beams, Figure 2, were pre-stressed by means of pre-tensioned horizontal iron bars, completely independent of the cast iron section (Zorgno 1988, 139-61).

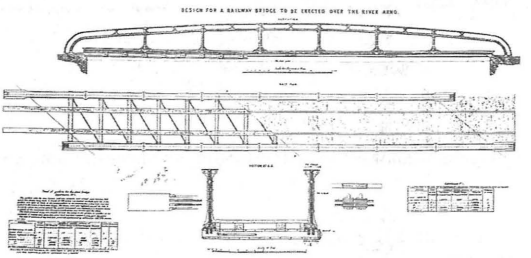


Figure 2
Beam in prestressed cast iron in the bridge over the Arno at Camaioni, designed in 1848 by Robert Stephenson and Charles Heard Wild (Zorgno 1988)

And it was precisely this experimentation with prestressed cast iron, a material extraordinarily similar to concrete, at least in terms of strength behaviour, that had the most analogies to early attempts to prestress concrete by means of iron tie-rods.

While Doering's patents of 1888 are often cited, François Chaudy's work is lesser known. Yet already in 1894 it clearly foreshadowed the potential of post-tensioning by threading tendons through blocks of concrete. Chaudy, who based his reasoning on the well-known concerns regarding the inevitable cracks in concrete in the tension zones, suggested forming the beam, Figure 3, in concrete only, with a canal along the bottom for housing an iron tie-rod, to be put under tension, once the concrete had cured, by tightening at the ends of the beam (Chaudy 1894).

The proposed solution had no real possibility of application because, as is well-known, the allowable tensions for reinforcing available on the market at that time permitted such modest amounts of elastic stretching that it would be rapidly cancelled out by concrete shrinkage and by slow deformations.

Yet the idea of pretensioning reinforcing bars was not discarded, despite the lack of success due to technological limits. Concerned about the durability of the reinforcing following cracking in the concrete

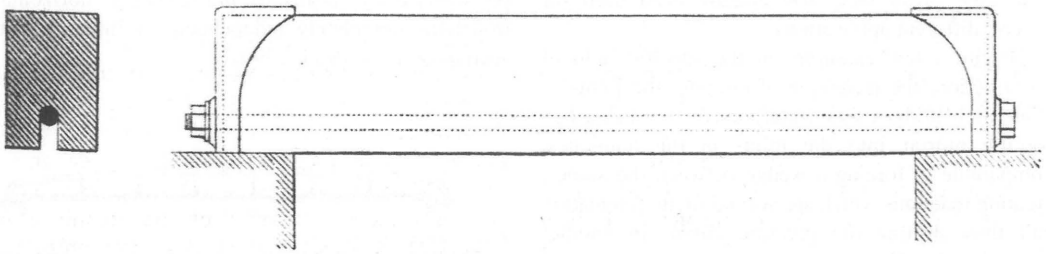


Figure 3
Concrete beam type, to be prestressing by means of a tie-rod, according to ideas by F. Chaudy in 1894 (Chaudy 1894)

in areas under tension, in 1907 Matthias Koenen — the first to have carried out systematic experimentation and to have proposed a design method for reinforced concrete— invented a rudimental device for putting reinforcing bars under tension before concrete placement. His «stretching» procedure, Figure 4, was meant to increase the «tonicity» of the iron and thus, all loads being equal, result in less deformation, thereby reducing the risk of cracking of the surrounding concrete.

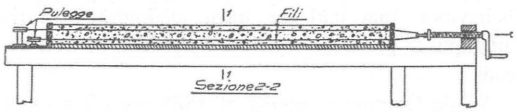


Figure 4
Device by Matthias Koenen for tensioning the reinforcing rods before placement of the concrete, 1907 (Cestelli Guidi 1947)

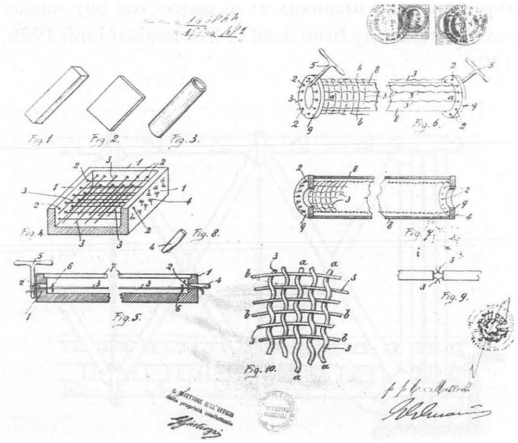


Figure 5
Italian patent n. 166844 by E. Mezzetti: *Innovazione nei sistemi di armatura del cemento*, May 20th 1918 (Archivio Centrale dello Stato)

With the same goal in mind, an Italian in 1918, Ernesto Mezzetti, patented an easily applied system, Figure 5, using wedges and keys for stretching the iron reinforcing bars. As an illustrious antecedent to his system, he cited the traditional practice of forcibly stretching the tie-rods of arches and vaults (Mezzetti 1918).

Modern prestressing: systematic deformations

As is well known, Eugène Freyssinet is the structural engineer who developed modern prestressed concrete. Beginning with his famous series of segmental arch bridges —Veurdre, Boutiron, Châtel-de-Neuvre— from around 1910, the Frenchman experimented with an original technique of striking centring by distancing the two symmetrical semi-arches using hydraulic jacks positioned at the crown and operating horizontally. His first prestressing system, known as the «systematic deformation method», hinged on this technique.

"The idea behind this method ,wrote Freyssinet, consists in not accepting the elastic state of a structure as the necessary result of its usual conditions of implementation, but, on the contrary, to endeavour to discover, by means of an initial deformation

artificially imposed on certain elements, if it can be favourably modified» (Freyssinet 1928, 1033).

In the case of arch bridges, it is known that at the moment of striking centring, the elastic deformation, the inevitable distancing of the abutments, the shrinking of the concrete, and temperature variations, all contribute to inducing a change in mean fibre direction, which, non longer coinciding with the lines of pressure, determines ulterior stresses. Freyssinet's method consists in correcting, by means of jacks, the curve of the centres of mass, so that once again it coincides with the pressure curve, cancelling out these parasitic loads. Artificially induced stresses were introduced in the structure, in the opposite direction of the design loads, in order to best take advantage of the strengths of the material.

The technique was without a doubt ingenious. However, added Freyssinet, "the use of indirect methods for creating a priori deformations which are to be equal and opposite to predicted loads is a very delicate task which must be carried out only by experienced engineers» (Freyssinet 1928, 1033).

Only a few engineers in Europe took up the challenge launched by Freyssinet. Among these was Eduardo Torroja. During the construction of the Tempul Aqueduct in 1925, he confidently made use of hydraulic jacks to correct the shape of the structure deformed under normal load conditions.

In Italy, only Eugenio Miozzi, an engineer for the Engineer Corps in Bolzano, had the courage to follow the footsteps of his two famous colleagues. In 1930, having passionately studied Freyssinet's accomplishments, Miozzi had a chance to experiment with a personal variation of the technique of systematic deformation in his non-reinforced concrete bridge over the Sojal river. He used jacks to re-centre the pressure curve, but instead of raising the arch by acting upon the crown, he lifted it just as efficiently from the impost (Miozzi 1930).

Development of prestressed concrete in Europe

On October 2, 1928, Freyssinet registered a patent in France —and a year later in Italy as well— in which he claimed the rights to a «manufacturing process of reinforced concrete elements» (Freyssinet and Séailles 1928; Freyssinet and Séailles 1929). One would never guess that behind this banal-sounding title lay a true «revolution in the art of building».

Freyssinet's prefabricated elements, Figure 6, were manufactured with straight reinforcing rods, pre-

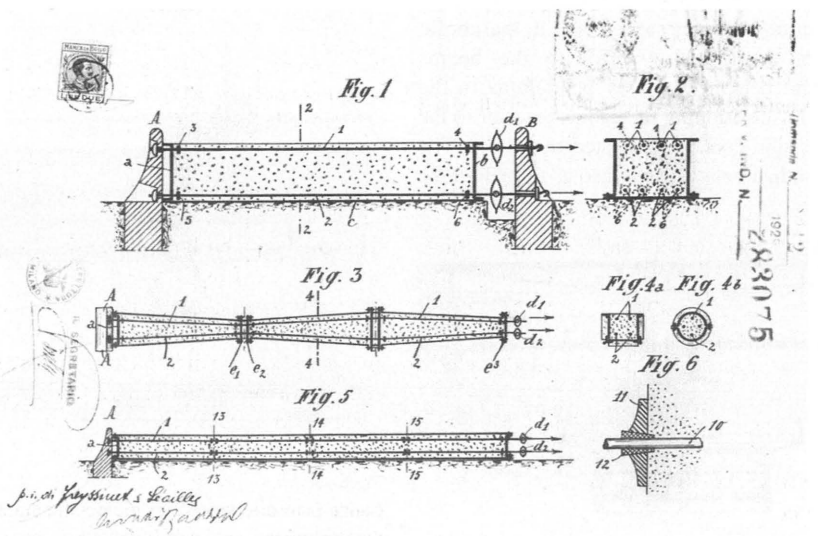


Figure 6
Italian patent n. 283075 by E. Freyssinet and J. Séailles: *Processo di fabbricazione di pezzi in cemento armato*, October 1st 1929 (Archivio Centrale dello Stato)

tensioned before the placement of the concrete. They were not merely pulled tight as with the many previous experiments, but rather, subjected to sufficient tensile stressing as to produce a significant amount of elastic strain. The tensioned rods had anchor devices for transmitting their stresses to the, by then cured, concrete.

In 1935, Freyssinet licensed his patent for Germany to the company Wayss & Freytag — already well-known for having bought Joseph Monier's patents for reinforced concrete fifty years earlier. Together with Matthias Koenen, they began the first systematic experimentation on the material. As always, the forward-looking company conducted a precise and expert evaluation of the system. The long experimental phase was concluded in 1939 with the construction of the first European bridge in prestressed concrete, a highway overpass with a span of approximately 33 metres. The project was by Emil Mörsch, technical director of Wayss & Freytag, in charge of all experimentation.

Another German, Franz Dischinger, the creator of the Zeiss-Dywidag thin vaulting system, claimed that he was the inventor of prestressed concrete, having also registered a patent in 1928 to that regard. In 1934, Dischinger deposited another patent for a system of beams for bridge-building. The beams, Figure 7, were to be prestressed using very large diameter braided steel cables in a parabolic conformation, positioned exterior to the beams themselves and held in place by pendulums to the cross beams. By positioning the cables exterior to the beams, the tension could be adjusted over time. The parabolic form had been designed so as to realign the stresses along the centre of mass of each section, thus resulting in a uniformly compressed beam.

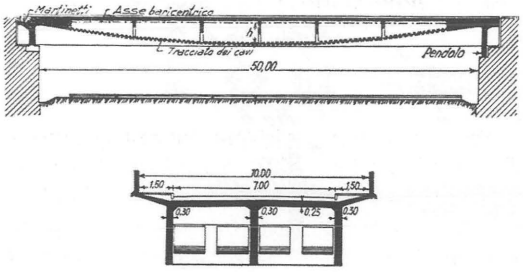


Figure 7
Prestressing system designed by Franz Dischinger in 1934 (Cestelli Guidi 1947)

Among the developments in Germany, where, in preparation for war, research aimed at conserving iron had been encouraged, perhaps the most easily applicable was a technique by Ewald Hoyer. His prefabricated floor beams were prestressed using very fine, adherent, piano wires (Hoyer 1939). Pre-tensioned close to the safe load capacity and without the need for anchoring devices, the wires immediately sparked curiosity in Italian journals as well, where they were published in April of 1939.

Developments in Italy: Gustavo Colonnetti's patent

The first true applications of prestressing in Italy mainly regarded concrete pipes. The prestressed concrete pipes manufactured by Vianini had already been the strong suit of the Italian delegation at the First International Congress on Concrete and Reinforced Concrete at Liege in 1930. The company in 1933 presented a new patent, Figure 8, which claimed the rights to a machine capable of prestressing the pipes using steel wire under tension: the technique consists in spirally wrapping and

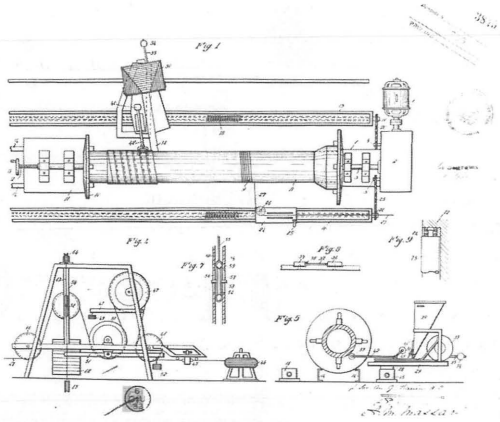


Figure 8
Italian patent n. 314685 by Guido Vianini & C.: *Macchina per fabbricare corpi cavi di materiale cementizio, fibroso o no, per rivestire tubi metallici con materiali plastici e per armare corpi cavi con armature metalliche in tensione*, June 6th 1933 (Archivio Centrale dello Stato)

weaving a steel wire around an already cured pipe, and then protecting it with a layer of fibre-reinforced concrete (Guido Vianini & C. 1933).

In June of 1939, the S.C.A.C., Società Cementi Armati Centrifugati, company further developed its already famous centrifuged concrete poles by inserting tensioned high-strength wires along their length, embedded into the concrete (SCAC 1939). The technique developed by SCAC, Figure 9, has clear analogies with the Hoyer method, not yet protected by patent in Italy.

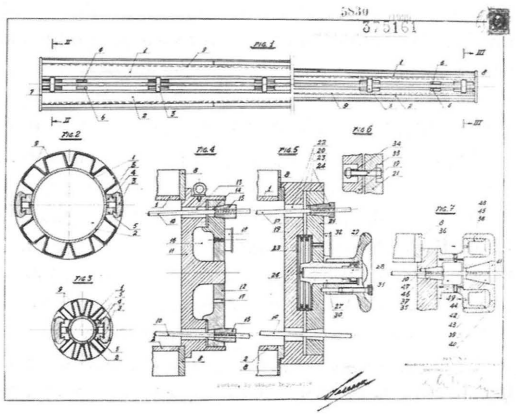


Figure 9
Italian patent n. 375161 by Società Cementi Armati Centrifugati SCAC: *Perfezionamenti nella costruzione di manufatti in cemento armato centrifugato con armatura sottoposta a tensione preventiva*, June 19th 1939 (Archivio Centrale dello Stato)

However, the first Italian patent for beams in reinforced concrete with pretensioned wires belonged to Gustavo Colonnetti. Over the course of the year 1939, Colonnetti published a long series of articles on the potentials of prestressing and its developments in Europe; in June of the same year, he held a conference at the Sorbone in Paris on the "coaction states", and during his trip abroad he probably had a chance to expand his knowledge of the Freyssinet, Dischinger and Hoyer systems; in September he published the already cited article on the design of prestressed beams; on the 12th of December he registered his patent, Figure 10, followed by another in January of 1940 (Colonnetti 1939c; Colonnetti 1940b; Colonnetti 1940a). Though the patent was based on ideas already present in the European patents, he distinguished himself for his highly original solutions.

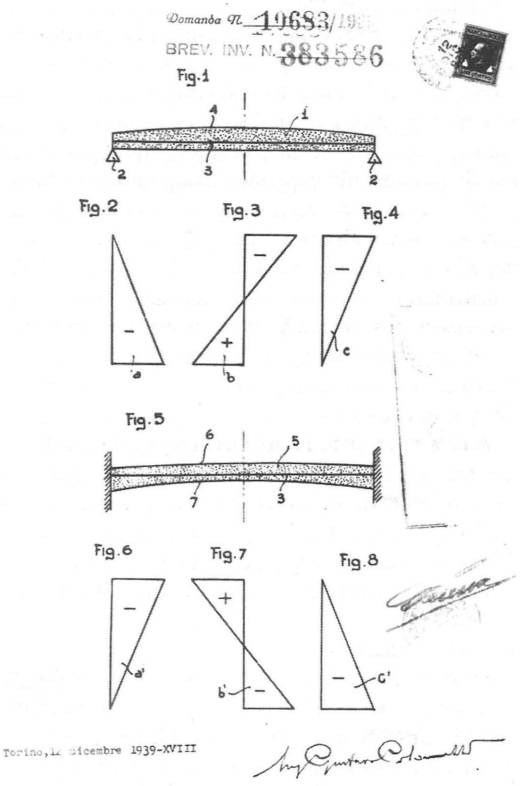


Figure 10
Italian patent n. 383586 by G. Colonnetti: *Trave armata ad armatura preventivamente tesa*, December 12th 1939. (Archivio Centrale dello Stato)

There were two particularly interesting aspects. The first is the form of the beam itself. Colonnetti designed an arched beam in which the height of the section changed constantly. His idea was to align the lower points in the kern of the sections of maximum positive moment, the upper points of the kern of the sections of maximum negative moment and the centres of mass of any sections of zero moment: this alignment also coincided with the line of action of the

resultant of the preventive tensioning of the tendons. In the beam thus formed, the static conditions of the arch were created, with the pressure curve contained entirely in the kern, but without thrust. The goal was obviously to make the materials work, each stressed according to its particular characteristics, at the maximum stress possible in all sections. The result is a beam of uniform strength which works like an arch without thrust.

The second original feature of the patent was the lack of adherence between the concrete and the tendons. Colonnetti did not follow the strategy of Dischinger, who positioned the tendons outside of the beam. Instead he embedded the tendons in the concrete, protecting them, however, with an isolating material which kept the concrete from coming into contact with the tendon: in this way once the concrete had cured, the tendon was free to move within the concrete and its tensioning could be delayed until the concrete had already completed most of its shrinkage. Furthermore, the tendons were positioned, unlike with the Dischinger method, in an excellent position with respect to the section for carrying out their task of pretensioning. Regarding the characteristics of the isolating material, Colonnetti proposed the use of thin metal foils, or more economically, by applying tar, bitumen or plastic cements based on rubbers, oils, and asbestos fibres, directly onto the tendons. In 1941, Colonnetti presented a simple system, Figure 11, for tensioning and anchoring tendons (Colonnetti 1941).

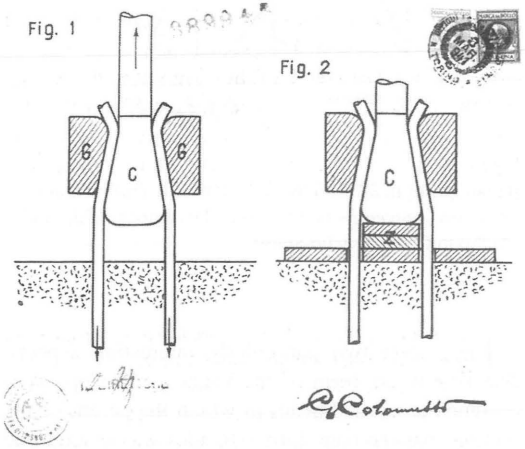


Figure 11
Italian patent n. 389946 by G. Colonnetti: *Dispositivo per la messa in tensione e l'ancoraggio delle armature nelle strutture in conglomerato cementizio*, March 3rd 1941 (Archivio Centrale dello Stato)

In the post-war period, the development of prestressed concrete substantially followed the path laid out by Colonnetti, though the tendons and not the beam took on a non-rectilinear configuration, sliding freely within specially shaped conduits.

But not even Colonnetti's immense enthusiasm could overcome the real limit to the development of prestressing in Italy: the unavailability of high-strength steel. A lack of prime materials, the incompatibility of Italian production lines, the impossibility of buying finished products abroad, not only because of economic problems but also because other nations in more favourable times had monopolised the market with long-term contracts — all these factors made serious experimentation impossible. Attempts by the Italian metallurgical industry —in particular Ilva and the Società Acciaierie e Ferriere Lombarde— to manufacture high strength steels from domestic prime materials resulted, unfortunately, in failure (Guzzoni 1942).

Nonetheless, stimulated by Colonnetti's work, new Italian patents soon arrived, including those by Luigi Magistretti (Magistretti 1940), Augusto De Fant (De Fant 1942), and Franco Mattiazzo (Mattiazzo 1942), Figure12, improving upon the techniques of tensioning and anchorage of the tendons in beams of prestressed concrete.

Experimentation soon followed in academic laboratories: in 1941, in the laboratory of the Construction and Bridges Institute of the Politecnico di Milano, Luigi Stabilini conducted load tests on partially pretensioned "Varese" type floor beams, having first built a special machine for tensioning rods to be incorporated in the concrete placement.

Industry was also very interested in the system. In 1941, the Società Anonima Cemento Armato Precompresso, Anonymous Society for Precompressed Concrete, or SACAP., was founded in Turin, encouraged by the engineer Giovanni Agnelli in order to favour development of the system (SACAP 1941). The SCAC company, having already experimented with its system of adherent wires in concrete poles, bought the rights to the Hoyer patents for beams, which had been deposited in Italy as well (Hoyer 1942a; Hoyer 1942b; Hoyer 1942c). They

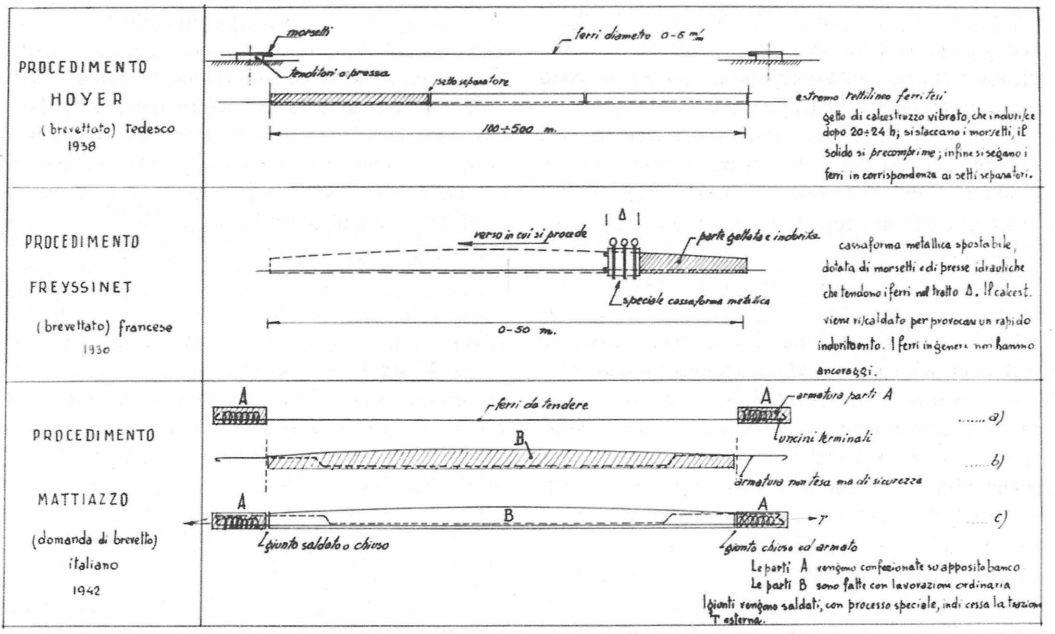


Figure 12
Comparison of the methods by Hoyer, Freyssinet and F. Mattiazzo in the Italian patent n. 402837 by F. Mattiazzo: *Struttura in calcestruzzo di cemento armato provvista di armatura metallica preventivamente tesa*, April 2nd 1942 (Archivio Centrale dello Stato)

built the first industrial plant for pretensioning in their factory at Monterotondo, making use of an «Ultracem»-type cement furnished by the Civitavecchia branch of Italcementi. Towards the end of 1942, they began experimental production in series of floor beams with an inverted T-section in concrete, prestressed with adherent wires (Cestelli Guidi 1947). However there is no documentation of the use of these beams, nor of any other structure in prestressed concrete, at least until the end of the war.

It was the war itself which restored a balance in the situation: the forced pause in large-scale building in general, the complete suspension of conferences and seminars, the irregular publication of books and journals, all favoured interest in the new technology.

The best engineers, aware of the new developments, took advantage of the interruption of design activity by conducting experiments in their own studios. In February of 1944, Riccardo Morandi appeared on the scene, registering his first patent which claimed the rights to a process for prestressing tendons by means of low voltage electrical current (Morandi 1944). Over the following years, this young Roman engineer would obtain exceptional results, redeeming the efforts of Colonnetti and all those who together with him had only been able to hypothesise the unattainable.

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Bridge-building and Industrial Revolution

Andreas Kahlow

The bridge at Coalbrookdale, the Halle au Blé or the Magdalen Market, Pont Ivry or the Carousel Bridge in Paris, the Hammersmith suspension bridge or Crystal Palace in London: wc could cite numerous examples of engineering feats that were topics of lively discussion at the time of their construction. Some of these structures have remained noteworthy, although they are no longer standing. Others make a grand first impression, but are soon lost in the forgetfulness of time.

Success and failure are bound up with values that are part of an elaborate communication process. Yet we may ask whether there are reasons for the abiding interest in some types of construction and the fading interest in others. What has remained significant up to today, and what might yet be rediscovered? The answer to these questions is relevant not only for the history of engineering and the preservation of historical monuments, but also for new construction projects.

Ministerial Archetypes

In Prussia regulations concerning construction projects were officially published in a series from 1830 to 1848 under the title «Bauausführungen des Preußischen Staats» (Building Descriptions for the Prussian State), to which we shall make frequent reference in this discussion. The instructions were directed by the Ministry for Finance and Commerce to Prussian building authorities. Their intent was formulated as follows:

> It is advantageous that architects engaged in construction projects gain knowledge of building practices concerning unconventional constructions that have been approved by the highest authorities. This knowledge not only contributes to his training, but also aids him in planning and completing his project in accordance with standard approved methods . . .

Something like a Prussian tradition in civic engineering, emphasizing the construction of useful and economical buildings, had already been developed by this time. The first such civic structures go back to the exemplary constructions of housing settlements in the vicinity of the Oder and Warthe rivers in the 18th century. Especially David Gilly (1748–1806) earned a reputation about 1800 for his technical «archetypes», which he managed to realised in spite of the oversight of the chief building administrations, the so-called «Oberbaudepartement» or later «Oberbaudeputation» (General Building Administration).

Archetypes were being sought at this time on account of the development of new materials (especially cast iron and wrought iron) and new construction methods, especially for bridge construction. The discussion of technical solutions could only take place by means of actual on-site experience, or else by means of detailed descriptions and technical drawings of the construction elements.

Because there were only a small number of exemplary buildings and because of travel difficulties (there being no railways), the availability of descriptions and construction details was of central importance. As yet there were only very few technical periodicals and engineering schools. How then did the communication take place, which led to the formation of archetypes or paragons?

We will address this question by looking at three examples illustrating the development of bridge-building systems in the 1820's.

The publication of the «Bauausführungen» began in January of 1830. The third assignation included, among others, the cast iron «Long Bridge» or «Lange Brücke» in Potsdam (built 1822–1825, plates 11–13), the Pipe Bridge or Röhrenbrücke over the Hammerstrom (built 1828/29, plate 27) and a suspension bridge in Malapane in Silesia (built 1825, plates 25–28) (Bauausführungen 1842). However, Förster's «Allgemeine Bauzeitung» (General Building Newspaper) of 1837 does not report on the suspension bridge (Förster 1837). The same is true of later assessments and reports concerning this bridge, showing that it did not fulfil the expectations of the Prussian General Building administration, which was oriented toward «archetypal constructions» (Malberg 1857–1859; Heinzerling 1870; Mehrtens [1900] 1984) . Let us first of all address the history of early cast iron bridges in Prussia.

Cast Iron Bridges

The beginnings of the Silesian iron industry at the end of the 18th century can be traced back to English influences. The director of the Silesian mining industry, the earl von Reden, directed his energies toward introducing new English technologies into the mining centres, especially the use of sand-molds and coke blast furnaces.

The very first German-language periodical addressed to construction and architecture, the «Sammlung nützlicher Aufsätze und Nachrichten, die Baukunst betreffend» (Collection of useful essays addressing architecture), was established in 1797 as part of the preparations for establishing the Berlin «Bauakademie». In its first edition the journal reports in detail on bridges made of cast iron. The first such bridge in Prussia had been built by the Scottish pourer Baildon in the province of Silesia in 1794. The periodical would only survive until 1806 and the Prussian defeat at the hands of Napoleon. Up till then it reported regularly on the progress of iron construction methods in Great Britain, France and Prussia. The copperplate prints included with the text give a clear impression of the changing construction principles.

In the early phase of cast iron bridges, there was a rapid change in fundamental construction forms. The most important factor was the experiences of the foundries that were beginning to develop cast iron parts. The demands of bridge planning played only a secondary role.

Because of the early difficulties connected with forming flawless arch structures, an early bridge in Stamford (Worcestershire), which had been built along the lines of the famous Coalbrookdale bridge, collapsed. The poor quality of the iron used in the ribbed arches was responsible for the mishap (Heinzerling 1870, 95). The English architect Payne chose to replace these unstable, long ribbed arches with much more stable cast iron sections. The individual parts of the vault structure consisted of relatively short cast elements (Riedel 1798). In 1793–1796 Rowland Burdon employed this principle for the Wearmouth Bridge across the Wear at Sunderland (span 71.92 m) (Sammlung 1798,1,1: titleplate; Heinzerling 1870, 95). The engineer Wilson was responsible for its planning and execution. Wilson also worked on a bridge with a span of 54.85 m over the Thames at Stains. In spite of numerous efforts at a repair, it collapsed in 1819. Telford also planned an enormous bridge in London using the same methods: span 183 m, height 20 m). The plan received much positive interest, but in the end it was not realised.

It was however not the «frame» construction form that would eventually take priority. Rather, it was John Nash's patented method of constructing bridges by means of slab-formed arch elements. The slabs contained flanges and were bolted together. J. Rennie's Southwark bridge of 1814–1819 became a widely recognised exemplary construction. As late as 1844, Stephenson's first draft for the Menai Railway Bridge with a span of 145 m was planned according this design. (Heinzerling 1870, 98).

The oldest construction principles are described in the «Collection of useful essays». But because of the repercussions of the Napeolonic wars, there is a gap

in the communication process beginning in 1806 and ending after the war with the publication of the writings of Langsdorf (1817), Röder (1821) and others. Here reference is made to new publications from France (for example Gauthey 1813).

In 1818 August Ludwig Crelle attempted to revive the journal under the title »Archiv der Baukunst» (Architectural Archive), and then again more successfully in 1829 with his «Journal für die Baukunst» (Journal for Architecture). Whereas the «Collection of useful essays» was affiliated with the inception of the «Bauakademie» (established 1799) and was edited by the members of the General Building Administration (Oberbaudepartement), Crelle's later journal was associated with efforts of Oberbaudirektor J.A. Eytelwein at reforming the academy in 1824.

J. F. W. Dietlein began to hold lectures on bridge building in the winter semester of 1824 here. They were published by Crelle in the period from 1830 to 1832. (Dietlein 1830–1832)

By examining the published version of these lectures (1830–1833) or some of the student lecture notes, we can arrive at a relatively good impression of what constituted an archetypal bridge construction in the context of Prussian civil engineering in the 1820's (Richter 1862).[1]

In 1830 J. A. Eytelwein turned over the leadership of the Prussian General Building Administration to K. F. Schinkel and the directorship of the Bauakademie to Christian Beuth, director of the Institute for Commerce (Dobbert and Meyer 1899, 45). The examples published since 1830 in the «Bauausführungen» assisted Beuth and Schinkel in their efforts to raise the standard of archetypal structural standards for construction administrators in Prussia. In a manner similar to Beuth's edition of «Vorbilder für Fabrikanten und Handwerker» (Archetypal Models for Manufacturers and Craftsmen, since 1821) dating back to his work as head of the Technical Deputation for Commerce, the field of engineering was now to be presented in an exemplary fashion for building administrators.

The «Long Bridge» at Potsdam

The first cast iron bridges in Prussia —Laasan (1794/96), Berlin (1797), Berlin-Charlottenburg (1801), Potsdam (1802) up to and including the constructions of the 1820's, the Frederick's Bridge (1822/23) and the Weidendammer Bridge (1823) in Berlin— employed the Coalbrookdale ribbing technique. The Long Bridge in Potsdam, planned by Günther and Becker, used the new methods of the Southwark Bridge. From the beginning it was designed to take a representative function and was discussed in the «Bauausführungen». The architectural colored drawings that are preserved in Potsdam give a clear picture of the high standards that were set for this structure.

Two iron bridges had been built previously in Potsdam. The first of these was the Helen's Bridge (1802), soon also called the Iron Bridge, and the second was the Berlin Bridge (1822–1824). The Helen's bridge had a length of 45 feet, which made it in 1802 the longest cast iron bridge in Germany. An examination of the historical documents reveals that an estimate of the quantity of iron required was made on the basis of test-castings, which shows that a precise calculation was not possible in advance (BLHA. I.HA Rep.96A/12J/Bl.44).

The latter was built virtuously simultaneously with the Long Bridge (1822–1825), but in accord with the older ribbed-arch method. The iron was ordered from the Royal Foundry in Gleiwitz in September 1821. Because of various mistakes (for instance, the plastering had not been taken into consideration), the individual elements had to be re-cast after completion in 1822. The iron was then transported to Potsdam in the summer of 1823. But then one of the arch sections fractured, so that the bridge was only completed in 1824 after a replacement arch had been sent from Gleiwitz. The finished construction consisted of nine arch elements in two large sections that were bolted together in the middle.

By comparison with the new iron casting technology, the role of construction was relatively insignificant up to the 1820's. Everything depended on the proficiency of the foundry workers at producing iron components that were not frangible. When malformed casting elements were bolted together, rapid temperature changes or severe strains could lead to «fissures or fractures of such pieces» (Vollhann 1823, 12–13).

With the construction of the Long Bridge in Potsdam the role engineering design took a predominant role for the first time. This was on

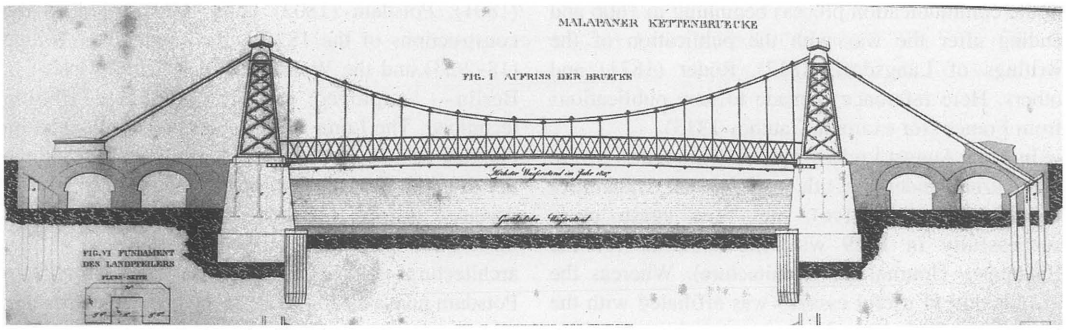


Figure 1
One of the cast iron arches of the Potsdam «Long Bridge» 1822–1825 (Müller 1889, 187). Müller used plate 12 of the «Bauausführungen» 1842

account of the innovative construction methods using iron plates. It was elaborated by the chief engineering inspector, Günther, who wrote most of the articles in the «Bauausführungen». Günther describes the construction with the aid of three illustrations. One of these drawings is remarkable for the fact that it is isometric, which was unusual in its day.

The structure included of a row of eight bridge sections, each of them 18.83 m in length, supported by stone piers. The passing of ships was made possible by employing a drawbridge at one end. All of the parts were bolted together, so that including the draw bridge a length of 166 m was achieved. Each bridge section consisted of seven consecutive arches, giving the roadway a depth of 9.5 m. One special feature of the bridge was the fact that each arch was formed of three slab-like iron elements. At their points of contact transvers transverse elements were added. This bridge in Potsdam «with its consummate form» would become an archetype for many railway bridges, of which the double-tracked Kinzig Bridge near Offenburg (built from 1843 to 1845) was the most famous. It consisted of five such arches, each spanning 12.66 m (Heinzerling 1870, 103).

The Long Bridge in Potsdam was dismantled and replaced in 1888. The erstwhile «archetypal structure», of which Heinzerling made a laudatory assessment in 1870, had revealed structural faults «from the very beginning», according to an 1888 report in the «Centralblatt der Bauverwaltung» (Müller 1889, 187–189). Even the first inspections after the completion of the bridge had revealed fissures and cracks in its superstructure. The last inspection before the dismantlement showed that 21 of the 56 elements cracked. Because of the rigid connections between the eight bridge sections and the foundations the entire edifice was incapable of accommodating itself to varying temperatures. If we assume that the assembly of the parts took place under normal summer weather conditions, then low winter temperatures must have led to contractions in the tightly bound connecting elements. The cast iron elements ripped out the joining bolts, so that many needed to be renewed after virtually every winter. The arches also broke. The inner arches at the center of the bridge suffered the greatest damage. And when they suffered damage, the pressure was transferred to the next arches as well, which now had to bear even greater force. The bulwarks of the supports were also put under so much pressure that the supports of the arches were entirely destroyed.

Of course, this led to the question why the builders of the 1820's did not take temperature tensions into consideration. After all, the influence of temperature on iron was already well known at that time, as the quotation from Vollhann cited above clearly shows. The answer is that the constructors of that day were using cast iron, but still thinking in terms of arch support systems made of stone. Stone is more flexible in the joints and the variation in its dimensions is insignificant in comparison with that of iron. At the other extreme are suspension bridges, where

temperature differences have considerable effects on the expansions and contractions of the support cables or chains. Even here one began with the concept that these new constructions were «systems», where the equilibrium needed to be determined. The different parts could withstand variant temperatures by balancing out the different forces. The problems were obvious especially for cable-stayed bridges, and not so much for «weighted suspension bridges», where the cables hang freely. —We can now address this matter by examining the development of suspension bridges.[2]

Suspension Bridges

What might well be the reason for the fact that our second example, the suspension bridge in Malapane, soon faded into forgetfulness? By comparison with other suspension bridges of the 1820's this structure managed to maintain itself very well over the years. Its span was only 31.56 m and could not boast the sensational lengths of contemporary English bridges. In an almost unaltered form, it still serves as a means of transportation in modern times (Pasternak 1996).

The bridge was built by the machine inspector Schottelius in the Malapane foundry in Silesia and opened on the 12th of September, 1825. An examination of its form reveals that it was constructed on the basis of an essay by Stephenson published in 1822 in the «Verhandlungen des Vereins für Gewerbfleiß» von 1822 (Stephenson 1822). At the same time it must have been built on the basis of information coming from Navier's 1823 essay «Sur les ponts suspendus».[3] It employed connected cast iron pylons in the form of portals and bore certain similarities to Newhaven's debarkment bridge at Trinity Piers (1820/21). Navier's essay gives excellent, indeed superlative depictions of the bridge. The suspension chains in the Newhaven Bridge did not slide, but were rather attached to the pylons. Sadly, this particular detail has never been accurately described or depicted, and was merely theorised in Navier's text. He compared the idea of moveable chains or chains that could be attached to rollers with those that might be attached to pylons and concluded that the latter idea was superior. This was then the idea that was employed in Malapane.

Navier's work was first presented in German language in 1824. Dietlein, whom we have already mentioned, discussed Navier's novel conception in his lectures series on bridge building at the Berlin Bauakademie in the winter semester of 1824 25 and published it in 1825 (Dietlein 1825). At the same time, the «Oberbaudeputation» (General Building Administration) made an assessment of the Malapane bridge and brought attention to certain defects.

In the first place the criticism concerned the chain anchors, which should have been placed lower and

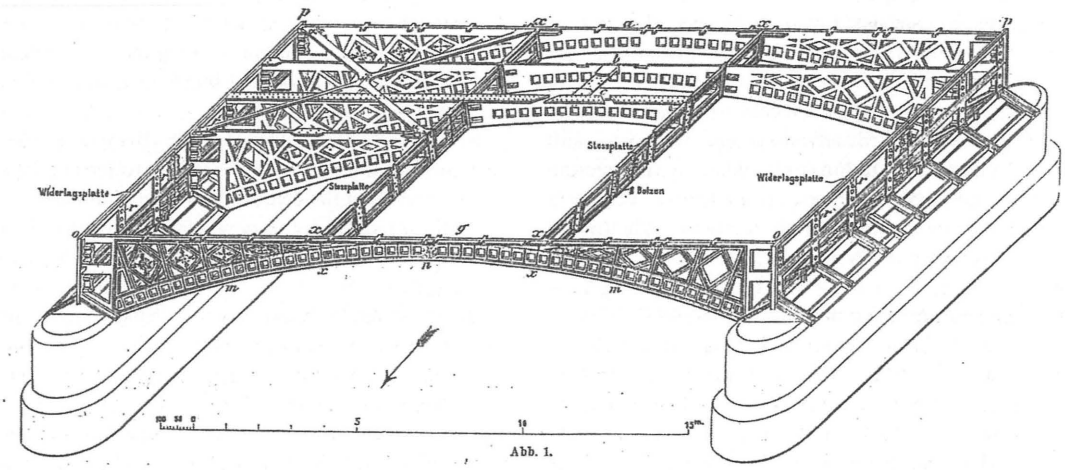


Figure 2
Malapane Suspension Bridge 1825 (Bauausführungen 1842 plate 25)

«under the abutments of the of theof the last arch», so that the anchors better would be able to take up the tensile force. Secondly, one could have spared the expensive underpinning of the «anchor pillars» (the foundations were not in danger of sinking, but of being ripped out). Thirdly, the saddles where the chains passed ought to have had mobile pivots (Bauausführungen 1842, 69). This idea had been introduced by the Union Bridge of 1819–20, which Stephenson had praised highly (Stephenson 1822, 123; Berg 1824, 21–22; Malberg 1857, 235). This design change had been suggested, but it had been forwarded to General Building Administration too late to be taken into consideration during construction (Bauausführungen 1842, 69).

It must be noted, however, that the comments made on the Malapane suspension bridge in the «Bauausführungen des Preußischen Staats» are dated 1832, and this suggests that they merely offer comments made after the fact.[4] It is no longer possible to confirm whether the first expert opinion of the General Building Administration of 1825 was actually formulated in the manner in which it was stated in 1832. But it is possible to show that the professional opinions concerning the value of early suspension bridges changed rapidly, so that after a few years they had a different status than at the beginning.

As an overview we can note the following chief events in the timeframe 1823 to 1832 in point form.

1) 1823: Through Navier's influence, the concept of a chain-line suspension bridge that is stabilised by means of its own weight became predominant. Inclined cables or chains came to be seen as disadvantageous. One was still unsure as to how to evaluate many engineering details (whether one ought to use weight or form to reinforce the roadway, whether to employ chain bars or cables, roller bearings or inflexible anchors for the chains, single or double pylons, the kind of hanger fastenings, or the means employed to attach the chains, etc.). —Navier offered precise drawings for four structures: S. Brown's Union Bridge at Berwick of 1819/20 (plates II, III), the Trinity Bridge at Newhaven (plates IV, V, VI), the two bridges for the island of Reunion by Brunel (plates VII,VIII,IX), and, Navier's own project for the «Pont des invalides» in Paris (plate XII) (Navier 1823)
2) 1824: Many chain bridges and suspension bridges are under construction throughout mainland Europe. The most well-known are Seguin's and Dufour's cable bridges, Traitteur's Panteleimon chain bridge in Petersburg, Schnirch's March Bridge in Bohemia (Berg 1824, VII). In Germany the first foot-bridge was built by Kuppler in Nuremberg. Many publications appear (z.B. Berg, Seguin, Burg). In the winter semester of 1824/25 Dietlein begins his lectures on bridges at the Berlin «Bauakademie».
3) 1825: Navier's work is translated into German by Dietlein.
4) 1825, 10th of August: the diagonal chain suspension bridge in Nienburg on the Saale river is examined. (Gerstner 1831, 470). On the 6th of December the left half of the bridge collapses, leaving many persons dead.
5) 1826: A sharp criticism of the Nienburg Bridge that had been written before the bridge's collapse is published in the «Verhandlungen für Gewerbfleiß» (Beuth 1826, 66).
6) 1826: Telford's Menai suspension bridge is completed. Chains over the saddle, resting on roller bearings
7) 1826, September: Just as Navier's great project from his book of 1823, the «Pont des invalides», was nearing completion, one of the piers shifted, leading to fractures which were then exacerbated by a break in a water pipe. The bridge is torn down.
8) 1827: The Hammersmith Bridge (under construction since 1823) with roller bearings for each of the chains is completed. It becomes the model for the new «Pont des invalides» that is built by the engineer de Verges 1827–1829
9) 1827: Krahe builds a cable bridge across the Oker river (Grunsky 1999, 132).
10) 1829, 31. of December: Schierlinger's chain bridge in Bamberg is opened for traffic (with ornamentation by Klenze, span of 64 m) (Röbling 1824; Anonymus 1830, 4). Like Navier's construction it had «isolated pylons» and soon after its completion, it displayed

fractures on account of its «immovable form» (Gerstner 1831, 469).

The disaster of Navier's bridge in September of 1826 did not throw suspicion on the entirety of his remarkable theoretical book of 1823, but certainly on some of his detailed solutions. This was true in particular for the rigid and inflexible saddle across which the cables were stretched. Since the completion of Samuel Brown's Union Bridge in 1820, there was a successful alternative: a moveable saddle on rollers. This kind of saddle was also used on Telford's Menai suspension bridge of 1826. The transition to individual arrangements of chains on rollers, which would become the standard solution, was adopted with Hammersmith suspension bridge in 1827.

One widely discussed question was whether the problems with Navier's structure were caused by the extreme weight of the over-sized bridge or by the lack of rollers and by the «independent» pylons. After its dismantlement, the engineer de Verges travelled to London to learn from the construction solutions of the Hammersmith Bridge (Heinzerling 1870, 190; Gerstner 1831, 465–468). It takes on an archetypal function, especially in the matter of the anchoring of the chains (Heinzerling 1870, 184) and the roller bearings (Gerstner 1831, 451 and 469). The new Invaliden bridge was completed in 1829 on the basis of this example, a result that raised the reputation of the Hammersmith.

Dietlein and Röbling

The question as to what information was available to planners and master builders is raised anew, if we look at some forgotten documents that have come to light concerning a chain bridge across the Ruhr river and concerning two plans for suspension bridges dating to the 1820's (Grunsky 1999). Some partial answers can offered by referring to Röbling's lecture notes from Dietlein's course on «Bridge-Building» in the winter semester of 1824–25, as well as supplemental notes added around 1830.[5]

We know very little about the building superintendent Bruns, who built the 1839 chain bridge over the Ruhr near Haus Laer. Grunsky's assessment of the building plans suggests that its measurements were influenced by Dietlein's German-language edition of Navier's work in 1825, as well as by knowledge of a project by Johann August Röbling designed in 1828, but never brought to fruition. We can conclude from Bruns' bridge, which is still standing, and from the relevant building plans that it was modelled after Marc Isambard Brunel's 1822 structure on the Island of Reunion, since it was a lightwight construction fitted with reverse chaines. Another detail, the cast iron pylons, were similar to those of Trinity Piers Bridge near Newhaven (1819–1820, built by Samuel Brown), just as the pylons of the suspension bridge at Malapane. Both construction forms had been drawn up by Navier, along with detailed descriptions.

A further discovery by Grunsky concerns two plans for a suspension bridge in Höxter, dated the 16th of December, 1824 by the building superintendent Eberhard, who was also working in the Prussian province of Westfalia. These drafts were also based on knowledge of Navier's reference work and of the Trinity Bridge in Newhaven, as well as Navier's own project for the «Pont des invalides» (of which Dietlein failed to provide an illustration in his translation).

Furthermore, the drafts for a suspension bridge across the Ruhr near Freienohl planned around 1828 by Röbling (89 pages) include a variant in Navier's style, but with decisive differences: a rigid roadway and displaceable chains, as well as a variant on a wire rope bridge. Here again work proceeded on the basis of a knowledge of Navier's book of 1823 or Dietlein's German version of 1825.

Röbling's lecture notes of 1824–25, as well as his later supplements, reveal how and why the perception of the suspension bridge changed substantially in such a brief time frame of five years. Röbling went to the Academy in the spring of 1824. Here he attended the lecture course by Dietlein on bridge building, which dealt with stone, wood and cast iron bridges. It also included a discussion of suspension bridges and Navier's method of calculation.

Although the printed lectures were primarily descriptive (the mathematical calculations were allready given in the translation from 1825), several remarkable new theoretical insights appear. In his printed lecture, Dietlein distinguishes between the basic principles of the diagonal chain bridge and the suspension bridge. Although the mishap of the Nienburg Bridge had already taken place, which

might lead one to think that he would put the diagonal chain variant in question, Dietlein gives no priority to either of the principles. In the meantime, Navier, who was responsible for the negative opinion of diagonal chains, had lost his reputation in the field of engineering practice.

Saint-Venant complained about the regrettable, even dubious discussion since the 1820's that there might be an «antithesis» between theory and praxis in the field of technology. The chief cause of this false claim was the misfortune of the «Pont des invalides» (Navier 1864, xviij). In point of fact, the subject of suspension bridges was largely discussed in the 20's outside of Great Britain and America by mathematically oriented, younger students, who for the most part had little experience in construction. Konrad Georg Kuppler, who built the Nuremberg chain bridge in 1824, taught mathematics and mechanical engineering at the Polytechnical School in Nuremberg (Grunsky 1999, 101). The building inspector Eberhard was judged by his superior, the Oberpräsident von Vincke, to be too «inactive» in supervising his building task force and preferred that he devote himself to calculations (Grunsky 109). Adam Burg was at first Assistant Professor and then Full Professor of Mathematics (Rühlmann 1885, 412) at the Polytechnicum in Vienna. In 1828, Röbling was still a young, inexperienced building administrator of 22 years of age, but with excellent mathematical abilities.

And yet with time, the traditional opinion that a good engineer was someone who had developed a reputation for building stable structures was replaced by a judgement based on the capacity to calculate all potential elements. In 1829, Bandhauer published a vindication of his work on the collapsed Nienburger Bridge. He defended himself with the claim that his bridge had not been built for such a large crowd of people. This led Gerstner to defend Bandhauer and to make positive remarks about the diagonal cable bridge (Gerstner 1831, 471). In a similar fashion, Navier was defended by the claim that his misfortune was caused by a broken water pipe and the hostility of the city administration in Paris (Prony, G. 1837, St. Venant 1864).

On the other hand, the mathematician and engineer August Ludwig Crelle, who edited the «Journals für Baukunst», clearly cautions builders from preferring suspension bridges to traditional building forms. He lists their disadvantages, in particular concerning safety and durability. He notes that «here and there a predilection for this form seems to have arisen, . . . with the consequence that based on this prejudice, it is actually preferred to other kinds of bridges» (Dietlein 1830, 462). An indirect reference to the Nienburger incident is made: «It is not merely folly, if a construction puts human life in danger, merely in order to realise a project that requires clever algebraic calculation» (Dietlein 1830, 464). Crelle demonstrates in his commentary on Dietlein that the loading cases were in fact quite different as in the calculations being used: Even the conventional material tests for completed structures cannot in fact give a realistic assessment of sudden impact loads or of accidentally occurring fissures in the materials being used. Crelle anticipated reductions in strength by means of «incessant vibration» (that is, fatigue) and concluded that the security of bridges was «being assessed purely arbitrarily» and that «there is no rule available» for calculating it. «The concern . . . to build bridges economically» often leads to the acceptance of inadequate safety factors factors of safety («multiplicators») (Dietlein 1830, 463).

In spite of Crelle's sceptical, but justified criticisms, there had in fact been considerable progress since 1823. So for example, testing materials by means of hydraulic presses had become standard practice (Stephenson 1822, 127): In Malapane this method was used to test the chains (Bauausführungen 1842). In his lectures, Dietlein does not discuss the technological and construction details, but he does refer to the fundamental distinction between «tensile» and «suspended» constructions, whereby, as we noted above, he does not criticise the diagonal chain principle. But it seems that the principle of «reinforcement through bracing» was being perceived more and more as a progressive construction method. Dietlein states for instance that the roadway in a cable stayed structure has to be so stiff, that it should not be «stretched or . . . pressed together» (Dietlein 1830).

Röbling's Lecture Notes and his Suspension Bridge

Dietlein states in his lectures that the primary condition of the diagonal chain bridge is the

construction of a rigid roadway, whereas the suspension bridge depends on weight (Dietlein 1830, 444). For Röbling, who may well have heard this opinion in Dietlein's lectures, this is a very important stipulation. He emphasizes the faultiness of the principle: «reinforcement through weight», which had directed Navier. Although he knew that suspension bridges are liable to suffer greatly from changable pressures (varying winds and travel loads), Navier took ont he challenge of designing a difficult construction with his «Pont des invalides», which needed to withstand high tensions on the chains and their abutments.

Röbling took a different approach with his Freienohl project. He reinforced the roadway and yet at the same time strove for movability of the chains by means of roller bearings and by avoiding mutually interactive connections between the chains. The distance of the chains between the pylons is greater than the breadth of the roadway. The inclination of the suspensions adds to the lateral reinforcement. By contrast to the Union Bridge, he did not couple the chains together: «each line of the chain should be able to move without external force and maintain its balance within itself», as Grunsky writes, citing Röbling's report (Grunsky 199, 135). The parallel chains were not to be bound to one another, so that they would not jam each other when temperatures changed.

We have good reason to believe that the collapse of the Nienburg Bridge was at least in some measure caused by a load shift caused by temperature variation in the triangular cable-system. (Roik 1986, 4). Since the collapse occurred at 8 p.m., we can assume that cooling air brought about an unequal contraction of the inclined iron chains. The roadway of the structure at Nienburg was not backankered in itselfto itself., consequently it did not have stiffness independent of the suspension construction. In the manner of weighted suspension bridges, the suspension cables were connected to the guy cables, which were in turn anchored to the base. This led to some unclarity in the static relationships.

Unfortunately, we do not know if Röbling made an assessment of the Nienburg accident. But the remark we have noted above shows that he had an intuitive feel for the connection between the structural estimation of a bridge and the tensions produces by temperature and loading variation. He disputes Navier's claim that a complete separation of the chains leads to oscillation of the roadway. This objection is insignificant and the reasons for introducing this practice are of greater importance for Röbling. «In my opinion, the reinforcement of the roadway should not be sought by the alignment of the chains, which cannot be achieved without force, but rather in construction itself» (Grunsky, 1999, 135). For this reason, Röbling attempted to solve the problem of oscillation by reinforcement of the roadway itself. He did not attach the hangers to the cross-beams in the conventional manner employed by Brown, Dufour and Seguin, but rather to the longitudinal stringers of the roadway, which resulted in increased stability (Röbling 1824, 372)

The design plans for Röbling's project at Freienohl are missing; only a few of the sketches have been found. But the supplemental lecture notes do help to augment his arguments, and they show where he got his ideas from. It is clear that Röbling developed many of his concepts and construction details through his knowledge of the Hammersmith Bridge, as he learnt of it through the «Magazin der neuesten Entdeckungen and Erfindungen» 3(1828) (Magazine of the most recent discoveries and inventions) (Röbling 1824, 370). Here the railing reinforcement marks one of the most significant innovations —an innovation that he developed further in his later suspension bridges in the USA .

Röbling did not lay his emphasis solely on mathematical calculation, but also on the intuitive-geometrical thinking that arose from the construction itself. We can see how a kind of «thinking in terms of reinforcement» evolved in his work. So for example, in his addenda to the lecture notes he adds remarks on «C. Steiner's system for an iron «bridge without abutments», where all the parts are accessible», together with a sketch, which he took from the journal «Der Künstler and Handwerker» 3(1828) (Röbling 1824, 360). The sketch illustrates a cast iron arch fitted with a tensile lower cord, forming a bowstring truss of six panels with cross bracing. The idea of using girders «without external abutments» was spread widely in the 1830's by Laves —using the same principle, but with the difference that they were executed in the well known lens-like form. Röbling added the form of the roller bearings in his notebook following the example of the Hammersmith- Bridge (Röbling 1824, 374).

He continued the notes by discussing the Bamburg suspension bridge. He remarked on its opening for traffic on December 31, 1829. On the next free page he made a pencil drawing of a for a suspension bridge «one thousand feet wide», which included a drawbridge for the passage of ships between a two-part pillar. Telford had already proposed such a 1000–foot suspension bridge for the Mersey- Gap near Runcorn back in 1813 (Stephenson 1822, 117). George Buchanan had also proposed a 400–foot suspension bridge at Montrose including a similar kind of drawbridge opening, which interrupted the suspended roadway (Buchanan, G. 1826). It is clear that Röbling introduced this unusual pillar construction in order not to reduce the stability of the roadway by means of interrupting it for boating traffic. The foundation elements of his giant bridge are elaborated with further drawings. He sketched a foundation with a base of about 50 by 50 feet and with a passable chain conduit. The guy chains are anchored not vertically, as in Navier's «Pont des invalides», but in the same angle as they came from the pillar.

Since the first wire bridge in Germany was built in 1827, Grunsky argues that the idea of using cables of wire-ropes form for large bridges was an particularly significant step (Grunsky 1999,114). This is certainly the case, especially if we take Röbling's later wire-rope bridges into consideration. However, it is also worth our interest to look at the sources for Röbling's ideas. For example, while we know that he had a copy of Dufour's book on the wire rope suspension bridge at Geneva (1824), we can only assume (albeit with good cause) that he knew of Berg's book about wire rope bridges including a report of the bridges of Seguin and Dufour (Berg 1824). It was published in Leipzig in 1824 and mentioned 1826 in the Journal of the Gewerbfleißverein in Prussia (Beuth 1826, 73), which means that it was widely known.

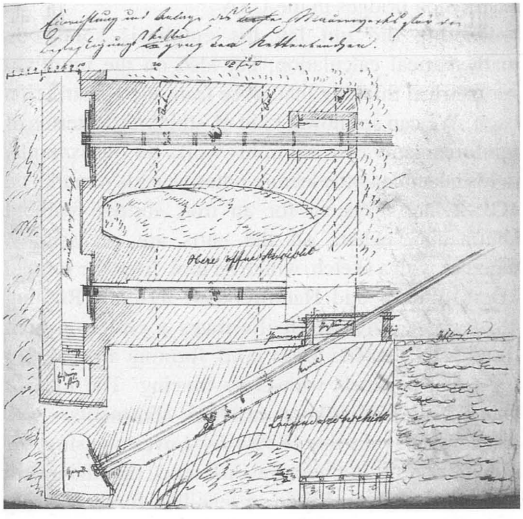


Figure 3
Foundation of Röblings 1000 —foot suspension bridge. Drawing from ca. 1830 (Röbling 1824, 411)

Concluding Remarks

The efforts of the Prussian General Building Administration to promote and encourage distinct archetypal constructions has led me to examine the question of the role played by assessments of new constructions in the communication networks of architects and engineers.

The chain bridge at Malapane, which at first served as the archetype for a new form of chain bridge, soon disappeared from contemporary consciousness —as the example of Röbling shows, who knew of the bridge, but did not consider it important. It was passed over by new developments. The journals and periodicals that experienced such a boom in the 1820's and 30's, with their lively discussion of the newest ideas, soon replaced the concept of «archetypes» that bore the stamp of official approval. We can also briefly mention the fate of the third type of an iron brigde, that was promoted as an archetype by the «Bauausführungen». This was the pipe bridge construction favoured by Reichenbach and Wiebeking, and which was discussed both by Dietlein and all of the other relevant publications of the 1820's, but which soon lost favour on account of stability problems of the numerous pipe elements. Many of these bridges collapsed or needed to be dismantled soon after construction. On the other hand, Polonceau's further development of this style of bridge construction in France had greater success. Polonceau built the Carousel Bridge in Paris from 1834 to 1836 by means of elliptical pipes of greater diameter. This served as a model for many road and railway bridges in France in the following years (Heinzerling 1870, 107).

At the same time, we should not underestimate the influence of the «Bauausführungen», as well as the journals and books in the years around 1830. They were produced just before many of these new structures were erected. At that time, even a small amount of information about new design methods was of great assistance, especially if they were combined with high-quality and detailed drawings. Precise engineering blueprints and the discussion concerning them arose at a time when engineers in central Europe had very few visual objects for developing their designs, and consequently they had much greater importance than in later years.

In matters pertaining to engineering construction, the «Bauausführungen» with their «archetypes» lagged behind actual developments in the 1840's, and in the next decade it was decided not to continue them. Instead, journals took their place, one of which had a special place at that time. The «Zeitschrift für Bauwesen» served the General Building Administration as a mouthpiece, substituting in a way for the «Bauausführungen des preußischen Staates». In the end, this administrative apparatus was not prepared to give up its influential role in supervising Prussian building construction.

Notes

1. The script of W. Richter's script is dated from 1862. The content of the convolute refers to the late 1820'ies. Dietlein's examples of cast iron bridges were: Coalbrookdale, Warmouth, Laasan, the «Bridges at Potsdam of the same construction», Wilson's bridge at Stains 1802, Cessart's Pont des arts at Paris 1803, Pont d'Austerlitz at Paris 1800–1806, the early truss bridge at Crou (St. Denis) 1808, and the pipe arch bridges of Wiebeking and Reichenbach.
2. It is interesting to note that the modern solution for maintaing the movability the supports was probably due to developments with the suspension bridge. One of the first such examples is roofing of the Walhalla at Regensburg, where Klenze introduced the first roller bearings in Germany. Can it be that Klenze's experience with the tears on the pylons of the Bamberg suspension bridge caused by immoveable connections for the chains —he had participated in its construction— led him to this innovation?
3. In Stephenson's book (Stephenson 1822, plate VI) the bridge is illustrated without diagonal chains, in Navier's they are included (Navier 1823, plate IV). Malberg writes that this were added subsequently in order to minimize vertical oscillation (Dietlein 1825, 3 and 5; Malberg 1857, 236)
4. The commentary is dated «February 1832», but the author's name is not given.
5. Röbling left Mühlhausen in May of 1831 and emigrated to America.

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The Fleischbrücke in Nuremberg: A stone arch bridge as an object for researching the History of Building Technology

C. Kaiser

This paper describes the aims and methodology of the Fleischbrücke research project currently in progress at Potsdam University of Applied Sciences and provides selected insights into the construction history —in particularly the competition process and the quality of the design drawings. The variant studies of the foremen —often contained in one and the same drawing— sharpened their insight into the force path, which lead to a robust, albeit from a modern viewpoint over-designed structure. However, due to its structural reserves it was able to cope with the changing demands from horse-drawn carts to heavy lorries, yet is nevertheless affected by the destructive force of water entering from the bridge surface and also horizontally. Refurbishment of the Fleischbrücke in accordance with guidelines for historic monuments is therefore urgently required.

Introduction

The Fleischbrücke is generally known as one of the most significant historic bridges of the early modern age. It was constructed from sandstone between 1596 and 1598 as a flat single-arch bridge under the supervision of «Ratsbaumeister» (council master builder) Wolf-Jacob Stromer (1561–1614) with a clear span of around 27 m and a width of 15.3 m. Up to 1700, the Fleischbrücke (Fig. 1) was the only bridge within today's German territory with a single arch exceeding a clear span of 18 m.

Master mason Jacob Wolff the Older (c. 1546–1612) and master carpenter and builder Peter Carl (1541–1617) also made significant contributions to the design and construction. The Fleischbrücke is in the same league as the Ponte Santa Trinity, the Ponte Vecchio in Florence and the Ponte di Rialto in Venice. Compared with the Rialto .bridge, the Fleischbrücke has an even flatter arch, advancing modern engineering skill even further. The Stari Most bridge in Mostar had a similar span, but with near semi-circular geometry similar to Roman bridges. The Ponte degli Alidosi dating from around 1500 has semi-circular geometry and a huge span of 42 m. The oldest preserved stone arch bridge, built 595 —605 in China, has a similar span, but a flat arch: The Zhaozhou bridge in Hebei province is classified as a World Heritage Site (Table 1).

State of the structure

The Fleischbrücke has survived centuries largely undamaged. Whilst the air raids of January 1945 destroyed approximately 90 % of Nuremberg's old town, the Fleischbrücke only suffered damage to parts of the parapet and the bay (Fig. 2).

The load-bearing structure still exists in its original substance. Interventions did, however, occur. In 1928, for example, water pipes were installed in the indented bridge section. After the war, parts of the southern abutment including the slanting piles were demolished during the construction of a flood relief tunnel. The

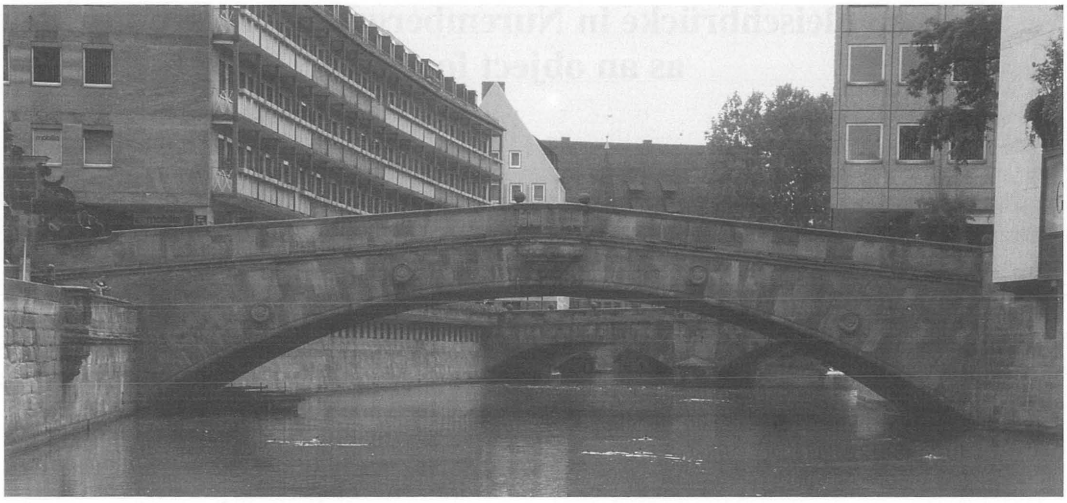


Figure 1
The Fleischbrücke from the west, June 2002. Photo: Kaiser

Table 1. Rise-span ratios. Data from different sources vary, see also http://www.structurae.de

Bridge	Location	Span l of the largest arch [m]	Rise h [m]	Rise ratio h/l 1 over
Zhaozhou Brücke (An Ji, Anji)	Provinz Hebei	37,02	7,23	5,12
Ponte Vecchio	Florenz	30	4,4	6,82
Ponte degli Alidosi	Castel deI Rio	42,17	19	2,22
Stari Most	Mostar	28,69	12,02	2,39
Ponte Santa Trinita	Florenz	32	4,57	7,00
Ponte Rialto	Venedig	28,8	6,4	4,50
Fleischbrücke	Nürnberg	27	4,2	6,43

space between the flood relief tunnel and the abutment was back-filled with concrete. The refurbishment of the visible surfaces in the 1970s has to be seen as a problematic intervention. The eastern elevation consists almost entirely of replacement stone. The Fleischbrücke has been under a preservation order since 1974, but had already been regarded as a monument before then. Nevertheless, several interventions occurred without appropriate documentation.

In February 1999, icicles were discovered inside the arch, which led to the conclusion that water had found its way through the bridge structure. As a result, the «Landesgewerbeanstalt» carried out numerous investigations and produced a first report (Stolarski 2001), which provided initial data and statements about material parameters. The basic tenor of the report leads to a recommendation for urgent refurbishment, including structural repair and measures commensurate with the preservation of historic monuments, particularly complete sealing of the decking and of the underground abutment components. The lower authority for the protection of

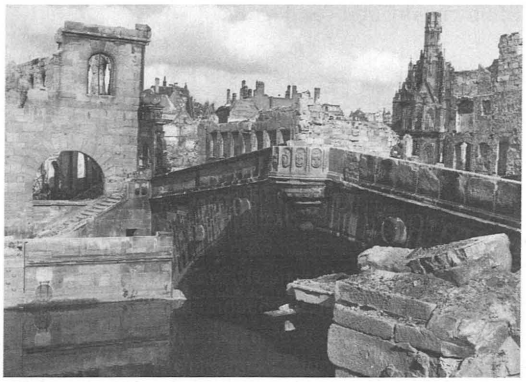


Figure 2
Destruction in 1945, the Fleischbrücke from the south-west. StadtAN: FiF3

historic monuments and the Bavarian state department for the preservation of historic monuments have been involved.

The research project

Preliminary remarks

Why is there no monographic treatise about this bridge, neither about its structural design, nor about its architectural design and effect? After all, following its completion historians and chroniclers beyond the European region praised it as a grand structure. The decoration is sparse. A cornice and a type of bay in the centre of the bridge with a stone patrician coat of arms, four stone rosettes on each side and the «Ochsenportal» gate connecting the bridge with the «Fleischhaus» provide some structure. The bridge itself integrates unspectacularly into the townscape. It is austere and simple without much decoration, following the council specification for town houses (Mulzer et al. 1954, 50–51).

An example for the lack of public recognition is a city guidebook for tourists covering the historic mile in Nuremberg, which is currently available on the internet.[3] Visitors are guided to 35 stations. Each station has a page describing the respective historic «jewel» (usually rebuilt). The last station is the «Fleischhaus» at the Fleischbrücke. Whilst scarcely anything remains of the original substance of the former «Fleischhaus», some historical details are nevertheless reported. In contrast, the bridge is not mentioned at all.

Nevertheless, the Fleischbrücke has been described in a variety of publications, not least by Prof. Dr. Wolfgang von Stromer (1922–1999),[4] who stressed the significance of the bridge as an outstanding piece of engineering of the late 16th century. He saw his forefather, «Ratsbaumeister» Wolf-Jacob Stromer, as a «hitherto unrecognised great architect of European standing» (Stromer 1997, 179). Approximately 100 design drawings are in existence, scattered across different city institutions. Whilst they should themselves be seen as documents of historic significance, up to now they had not been systematically evaluated and recorded.

Aim and methodology

Within the research project «The Fleischbrücke in Nuremberg», two somewhat contrary theses were developed. The aim of the project is to demonstrate the functional relationship between them.

One thesis is a **historic** one:

— Over the centuries, the estimation and appreciation of the bridge has developed in such a way that for engineers it has become a model for the whole European region, but it has not gained the status of an art-historically significant structure such as the Rialto bridge.

The second thesis is a **structural** one:

— Notwithstanding the lack of structural-constructive calculations, the evaluation of the results from the building survey and the construction history show that the bridge not only met the direct requirements of its time, but could also cope with increasing utilisation requirements.

The examination has structural engineering/historic character, but work on the theses also requires techniques usually employed by historians such as source-critical approaches or by preservers of historic monuments such as creating an inventory.

The examination of the two theses initially leads to

the construction history, with necessary reference to the original, historic sources. The structure itself on the one hand provides information about facts that could not be gleaned from historic sources, such as the material properties, and on the other hand about current damage. The combination of the historic data with the material parameters provided by the Landesgewerbeanstalt Nuremberg (LGA) leads to the creation of structural models and to structural-constructive analysis. This aims to compare structural calculations from today's viewpoint with the historic techniques for determining the load carrying capacity. For the evaluation, both knowledge on the subject of «arched bridges» published in treatises preceding the construction of the Fleischbrücke and comparisons with any predecessor or successor structures were used. This leads to an evaluation from today's perspective and in the context of the time of construction (Fig. 3).

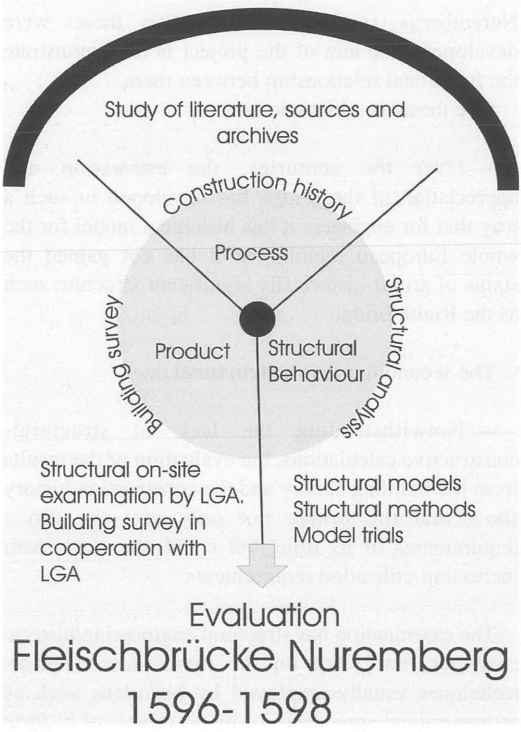


Figure 3
The research project

Bibliography and catalogues

The research project also includes a chronological bibliography of relevant publications, transcription of «Ratsverlässe» (council orders) and design drawings, lists of all the drawings found in different archives and institutions, and a comprehensive, separate catalogue part with photographs, maps, design drawings, engravings etc.

Digital archive

In future, the design drawings will be accessible within a digital archive in database form with retrieval management. This digital Fleischbrücke archive serves as a pilot project for the management of documents about historic monuments run by the state of Brandenburg at the Potsdam University of Applied Sciences, since it integrates the documents «virtually» in a single place, i.e. it separates the technical information from the historic carrier. This enables fast, comparative access.

Sources

Unprinted sources —the archive situation in Nuremberg

The Fleischbrücke was constructed during the era of the «free cities» under the jurisdiction of the free city building authority. Through the annexation of the free city in 1806, the city records and a large number of other documents came into the possession of the kingdom of Bavaria. The royal Bavarian archive was created, from which ultimately today's «Staatsarchiv» Nuremberg (StaatsAN) emerged. After the reinstatement of self-government in 1818, the state returned part of the archive material, including the files of the free city building authority, to the city of Nuremberg. These items formed the basis for the «Stadtarchiv» Nuremberg (StadtAN), established in 1872.

During the 18th and 19th century, various documents were deliberately weeded out. Via second-hand markets, some of them ended up in private collections and from there in city museums or the German National Museum (GNM).

Parts of the archive of the family of «Ratsbaumeister» Wolf Jakob Stromer were located at castle Grünsberg, including two large-format «Baumeisterbücher» (master builder books —BMB I and II).[5] After Prof. Stromer's death, they were donated to the Staatsarchiv.

Documents about the Fleischbrücke created since 1879 are held by the city of Nuremberg in today's civil engineering department.

There is no longer a complete official record about the Fleischbrücke, and it is no longer possible to determine what it may have contained. Along many other free city building authority documents, a repertory was also destroyed in the 2nd world war that provided information about the items held in the city archive. This necessitates a comprehensive search for individual inventories and other sources (e.g. «Ratsverlässe» (council orders) concerning the construction of the Fleischbrücke). In his «Baumeisterbuch» I, the «Ratsbaumeister» had indeed intended to gather drawings that would highlight significant stages of the construction process, such as the building site facilities, different falseworks and pile foundations. Stromer (1984) regards these volumes as town planning text books. However, neither the «Baumeisterbuch» nor the foremen attempted to present the Fleischbrücke retrospectively in a similar way to Perronet's description of the bridge at Neuilly: this comprised a complete documentation of the structure completed in 1782 including design drawings, material data, the construction process over the years, and more (Perronet [1788] 1987, 25–120). They left a clear field for historians. The master builders of the Fleischbrücke were not yet concerned about the endeavours expressed by Eitelwein in 1819 in his foreword to the German translation of Perronet's work, namely how important it is for other master builders that those «who have build a significant structure should not content themselves with completing the building successfully, but should also make known any difficulties encountered during the design, construction and execution» (Perronet 1820, a2). The historians showed little interest in structural engineering questions. For them, it was more important which coats of arms adorned the bridge and which inscriptions were shown on the commemorative coins that were placed with the foundation stone.

Publications

In the preparation of a bibliography about the Fleischbrücke, the passing-on of wrong information was also pursued, for example incorrect spans[6] or the alleged extreme settlement after removal of the falseworks that was quoted repeatedly.[7] Who was seen as the actual builder has also changed in the course of time. Up to around 200 years after its construction, Peter Carl was named as the builder. In the meantime, through the publications of Prof. Stromer, the Fleischbrücke has become the «Stromer bridge» —the bridge of «Ratsbaumeister» Wolf Jacob Stromer— (Diefenbacher and Endres 2000). After all, according to Stromer (1984, 80), it was not only constructed under the supervision of Wolf Jakob Stromer, but he personally found «completely new and independent solutions» for any problems that were encountered. Doubts are also expressed about the model character of the Rialto bridge reported in several sources (e.g. Mislin 1997, 289).

Building survey

Apart from the historic sources, the structure itself provides information. For example, the drawings do not show unambiguously whether the arch stones or the joints are wedge-shaped, because there is no drawing showing a section of the arch stones. Proof of the slight wedge-shape was found at the western elevation of the structure in stones that can deemed to be original due to their weathering.

The joint width or the stone bond in longitudinal direction were established during the survey of the underside of the bridge carried out jointly with the LGA (Fig. 4), which also included changes and damage to the structure and forms an essential basis for the refurbishment.

Construction history

The Fleischbrücke had special significance, since seven European long-distance trade routes met in Nuremberg, with the Fleischbrücke at their intersection. It carried the heaviest urban and transit traffic (Stromer 1988, 162). After the wooden predecessors of the Fleischbrücke had been destroyed

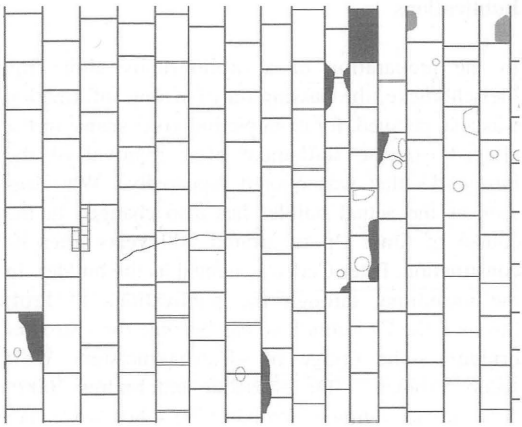


Figure 4
Section of the underside of the bridge, March 2002, including a survey of the cracks and other damage, joint widths, brickwork and concrete seals, etc. The stone rows in transverse direction are perpendicular to the centre-line of the bridge. There is no evidence of a regular bond. LGA, Kaiser

by fire or floods, a two-arch stone bridge was constructed in 1487.

In 1595, floods damaged or destroyed all of Nuremberg's bridges. Damage to the Fleischbrücke was such that it was decided to demolish and rebuild it. The council invited bids for a competition, in which more than 20 masters that are known by name took part, 16 of which were from Nuremberg (Pechstein 1975, 74).

Written proof of the technology transfer in terms of bridge construction can be found in the above-mentioned «Ratsbaumeisterbuch I» in form of a letter in Italian from the Florentine architect Pietro Cecini dated 30 May 1597 (Fig. 5), which commences as follows: «One will be able to build the bridge for the city of Nuremberg with a single arch with a span of 90 to 100 cubits . . . ».[8] He also mentions the Ponte Trinita,[9] a profile drawing and a plan view of which he says to have sent. Yet by the time the letter was written, the plans for the design competition had already been submitted, and without actually announcing a winner Peter Carl and Jacob Wolff were asked to carry out the work under the supervision of «Ratsbaumeister» Wolf-Jacob Stromer. Furthermore, the council had already decided that the rise of the arch should be 15 shoes.[10]

Nevertheless, we will initially examine the design ideas of the competition participants. The master builders and foremen of the «Peunt», the city of Nuremberg stone yard, had special instructions to protect the bridge from floods by a variety of measures (Reicke 1896, 573). A suitable structural measure for relieving the flood problems is a larger flow section. It is therefore not surprising that a recurring idea throughout the design reports is the desire to resist the floods and to provide free drainage for any ice that may accumulate. The decision for a single-arch bridge without centre pier was made for these reasons!

The choice of a flat arch, however, was based on the urban situation. For the tradespeople and their vehicles it was important that steep slopes should be avoided, and the residents did not want the entrances and windows of their houses and shops obstructed, which would have been the case if a high bridge with associated access ramps had been built (Falter et al. 2001a, 18; 2001b, 894–895). The effects of the new structure on the existing buildings are documented in a water-coloured pen drawing (Fig. 6).

Ultimately, the discussion resulted in a flat single-arch solution, which meant that issues relating to increased horizontal pressure on the supports and increased compressive strain at the apex had to be addressed. To what extent the foremen recognised

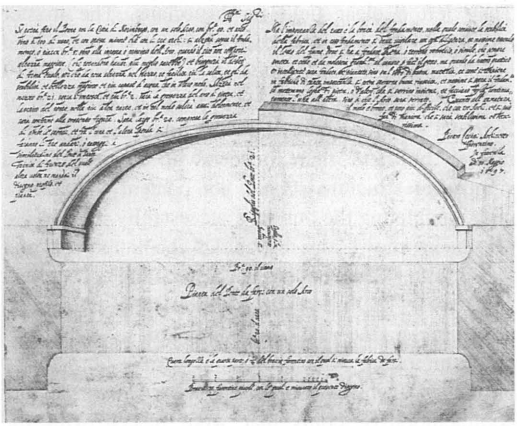


Figure 5
Letter by Pietro Cecini. BMB I

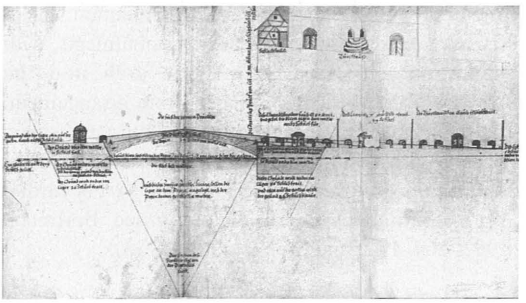


Figure 6
Basic design principles. Museums of the city of Nuremberg, collection of drawings: Hopf 5583

these problems and what structural and engineering solutions they used in response can be gleaned from the design drawings and reports.

Design process: Structural experience vs structural procedures

The know-how contained in treatises written prior to the construction of the Fleischbrücke

Whilst the dimensioning of the semi-cirular Roman stone arch bridges was based on experience, the master builders of the Fleischbrücke could have done with guidelines for dealing with the modified arch thrust resulting from flatter arch designs. The master builders were able to study Vitruvius' work (c. 84–10 BC), which reflects the Roman knowledge level, from 1548 after it was printed in Nuremberg and translated in German by Rivius. Whilst Leonardo da Vinci's (1452–1519) thoughts and sketches of the «Codices Madrid» about the dependency of the arch thrust on the shape of the arch had been put down on paper prior to the construction of the Fleischbrücke, they had not yet been published. In contrast, Leon Batista Alberti's (1404–1472) treatise «De re aedificatoria» had already been published several times in Italian. In 10 books about architecture, the broadly educated humanist wrote his own work, having previously studied the work of Vitruvius. In the chapter about bridge construction, he was the first person to formulate empirical formulae for dimensioning stone arch bridges in the sense of a geometric structural design (Mislin 1997, 274). However, the work referred to semi-cirular bridges, and so the rules were not directly applicable to the Fleischbrücke. Alberti's recommendation for the arch thickness was as follows: «The stones should have a thickness of no less than a tenth of the chord» (Alberti [1912] 1991, 209). A comparison with the dimensions of the Fleischbrücke shows that the designers chose a smaller thickness at the apex, and a greater thickness at the springings;

Fleischbrücke $4{,}00 \geq d \geq 1{,}35$ m, after Alberti $d = \frac{1}{10} = \frac{27}{10} = 2{,}70$ m.[11]

Dürer (1471–1528) provided rules of thumb in particular for the dimensioning of walls and foundations, but not for arches. Nevertheless, for the vaults in the castle he doesn't recommend semi-circular arches, but says: «These vaults should all have arches of approximately a third of a circle» (Dürer 1527).

In summary it can be said that the treatises did not provide adequate dimensioning rules for flat stone bridges. Vault theories did not emerge until later. The master builders had to rely on their experience, relevant model structures and innovative ideas.

Structural understanding in design drawings and reports

However, neither clues about model structures whose rise-span ratios one had to adhere to or could possibly dare to exceed, nor justifications for the choice of dimensioning have been passed down. There is clear evidence of the conflict between compliance with an absolute upper limit for the rise from a town planning point of view and the structural requirement for the arch to be not too flat for the given width of river.

In order to achieve a more favourable rise-span ratio yet keep the absolute height of the bridge low, the solution that was suggested repeatedly for the single-arch bridge appears logical: a reduction of the clear width of the river. Extending the piers into the river by up to 12 shoes, either on one side or equally on both banks was suggested several times, since one didn't yet dare to build even flatter arches. The suggested rise-span ratios varied between 1:3 and 1:6.3.[12]

There is little evidence of structural considerations. If structural problems are mentioned at all in the

different reports, they refer to the movement and the flexibility of the abutments. Peter Carl's opinion can be found in a kind of design brief on a water-coloured drawing (Fig. 7): « . . . The long main piles have to be fixed in such a way that no movement occurs between the grate and the piles . . . The piles inserted laterally into the ground should be seen as a strong strut providing support for the large load at the abutments, in order to minimise horizontal movement of the arch».

The need to avoid «movement of the arch» is also stressed by other foremen and shows that they saw divergence of the foundations as the most problematic load case for a flat arch. This finding is confirmed by Falter following an examination of the thrust lines (1996, 131, 156).

A dispute recorded in writing in a council order about a structural engineering solution confirms that Peter Carl tried to persuade the stonemason Jacob Wolff to build the arch with constant thickness, in contrast to the decision by the council to increase the thickness towards the abutments. However, the «Ratsbaumeister» instructed Jacob Wolff to build the arch as agreed, namely to «combine the spandrels with the arch, and to ignore the attempted interference by master Peter Carl».[13] Unfortunately, no justifications of the two designs were provided.

In combination with the evaluation of the different design drawings, the above-mentioned two examples demonstrate the debate about the force path and the structural engineering response. The intention was to increase the arch section towards the abutments, with integration and transition of the arch into the foundation, including a slanting stone arrangement. The ends of the slanting undercut abutments sit on slanting grates and slanting piles and appear to continue the arch into the ground (Fig. 8). For further information about the foundations see Borrmann (1992, 164–172) and Stolarski (2001, 33).

Single-arch vs. two-arch solution

Some of the competition participants initially offered several solutions, i.e. designs for a conventional two-arch bridge and a single-arch version. In some cases, the single-arch and the two-arch versions can be found one above each other on a single sheet, or the single-arch solution was dotted into the two-arch design. These different comparisons between «single-arch —two-arch», together with the associated verbal reports appeared to have served as a basis for the decision by the council and the «Ratsbaumeister».

Variation of the rise-span ratio

For single-arch designs, dashed lines show various versions from flat to semi-circular, from a rise of 10

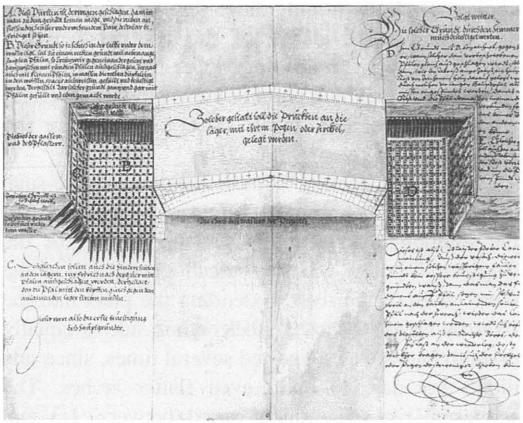


Figure 7
Design brief by Peter Carl. Museums of the city of Nuremberg, collection of drawings: Hopf 5584

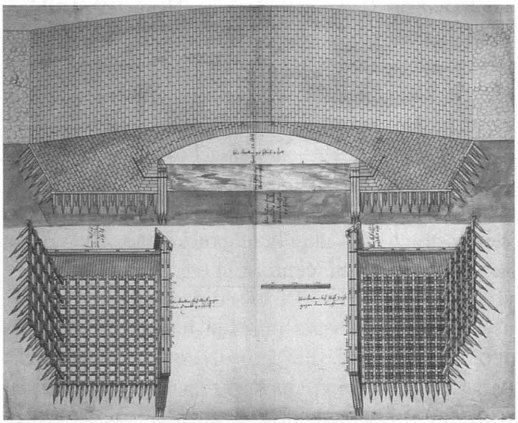


Figure 8
Water-coloured pen drawing of the pile foundations with horizontal and slanting wooden grates. GNM: HB 1406

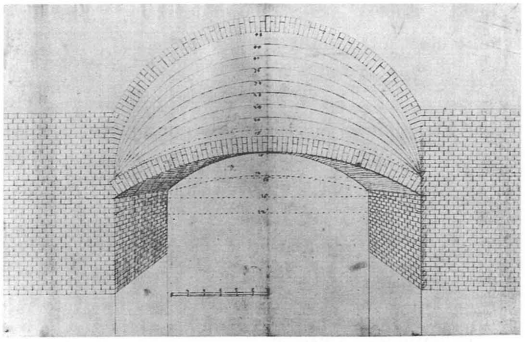


Figure 9
Diagram showing different rise values. GNM: HB 1427a

shoes to 48 shoes (Fig. 9). The drawer appeared to assess quasi visually what degree of flattening of the arch he considered to be feasible.

Another drawing shows flat arches with different rise on the left and the right (Fig. 10).

Variation of the integration of the arch in the area of the springing

The radial or slanting arrangement of the stones near the foundation is developed gradually in one and the same drawing (Fig. 11). Initially, only the arch is continued radially into the foundation (top), then the extended arch starts to become integrated into the abutment (centre), until the designer has convinced himself that a radially laid foundation will optimally transfer the arch forces into the subsoil (bottom). Studies about this radial stone arrangement across the whole body of the bridge can be found on many of the drawings. This corresponds to the actual bridge structure and is also continued inside the bridge, as confirmed by drillings carried out by LGA.

For the transition from arch to perpendicular masonry, different stone sections are tested in two labelled partial elevations (Fig. 12).

Radial masonry arch as response to structural considerations

The implementation of the complete arch structure including the abutments in radial masonry as an arch with increasing thickness is more demanding for the stonemasons than a ring of wedge-shaped stones and horizontal backing. After all, all stones of the arch have to be wedge-shaped. An evaluation of the design drawings leads to the thesis that the master builders, be it Peter Carl, Jacob Wolff or Wolf Jacob Stromer, considered it to be mandatory for «structural» reasons to use this stone section for transferring the forces into the subsoil and into the slanting piles as clearly as possible. We can only speculate whether they were aware of corresponding design drawings for the Rialto bridge. This radial placement of the stones even in the area of the foundation differs significantly from the usual method of constructing stone arch bridges, where

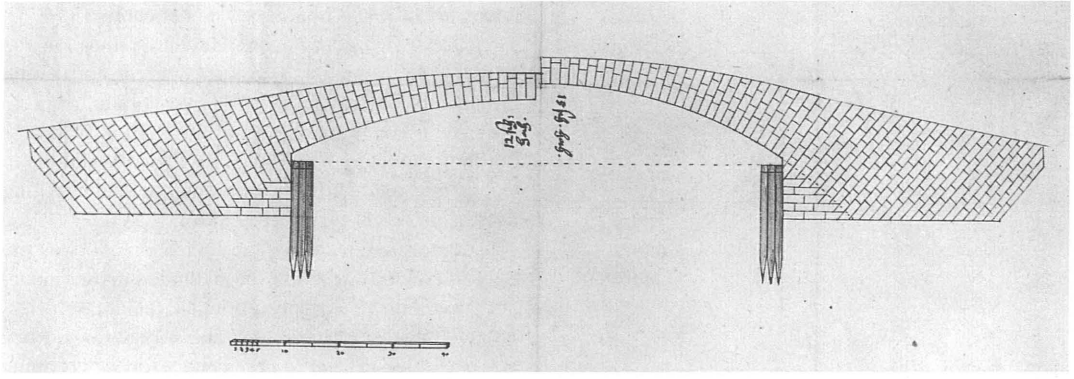


Figure 10
Diagram showing alternative rise values. GNM: HB 1417

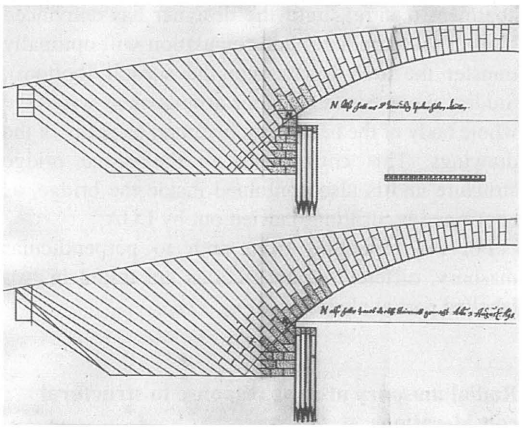


Figure 11
Three variations of the integration of the arch into the foundations. StaatsAN: Stromer archive B15, fol. 31 verso

the radial stone arch has uniform thickness, with the foundations and masonry layered horizontally.

Descriptions and drawings as means of structural engineering communication

The considerations that have led to the construction of the Fleischbrücke are examples of innovative

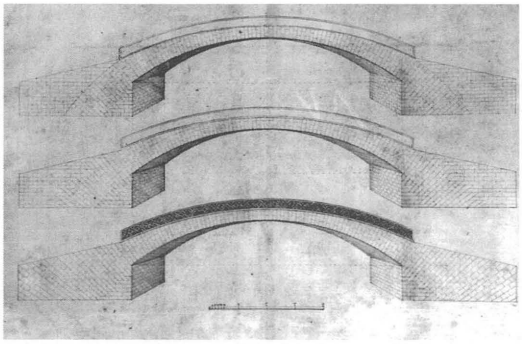


Figure 12
Jacob Wolff: Variation of the stone section in the area of the springing. Architecture museum TU Munich: Fleischbrücke Sig.6

understanding of structural engineering in the late renaissance in Germany:

- gathering, selecting, concentrating and substantiating of structural engineering know-how in the form of tenders,
- formation of a project-related structural engineering community,
- inclusion of qualitative structural considerations in the design process through verbalisation,
- systematic utilisation of drawings for design and construction variants.

Nevertheless, the structural engineering know-how gathered during the construction of the Fleischbrücke was not published after completion: with the completion of the Fleischbrücke, the structural engineering community disintegrated.

1821: FIRST TIME UNDER THE SPOTLIGHT OF ENGINEERS

According to Kurrer (1997, 87–114), the vault theories continued to develop with De la Hire, 1695, Bélidor and Couplet, 1729, A. F. Frezier, 1739 and Charles Auguste Coulomb, 1776, who calculated the limit values of the arch thrust with the aid of extreme-value and differential calculus, and Jakob Bernoulli, 1704, who determined the shape of the thrust line vault via the principle of virtual work.

None of these scientists have used the Fleischbrücke as a model. But around 200 years after its construction, practising engineers became very interested in it and it assumed model character. G. L. A. Röder was grand-ducal Hessian major of the artillery suite and «Chausseebaudirektor» of the province of Starkenburg. In his two-volume work he provides a «complete practical description of bridge building science according to the most reliable technicians and mathematicians and the best existing models of each type, written for road and bridge construction engineers». The Fleischbrücke was the only German bridge to be included as a model structure. For 35 European bridges, the author offers «a catalogue of some interesting bridges in Europe and their significant components, for determining useful bridge dimension ratios» in tabular form (Röder 1821, 194).

Röder not only provides the absolute dimensions, but also ratios relative to the span:

1. Height of the keystone / span
2. Thickness of the abutment / span
3. Thickness of the central pier / span
4. Height of the piers / span
5. Distance to chord / span.

At the time, bridge engineers still used compliance with these ratios as a standard for their construction, instead of static calculations.

In contrast, in his book «Theory of arches, revetment walls and iron bridges» chief architect Dr. Hermann Scheffler (1820–1903) calculated 40 bridges according to the principle of smallest resistance. The results collated in list form also include the Fleischbrücke as the only German bridge (Scheffler 1857, 76). In addition, Scheffler offers dimensioning tables that are no longer based on selected model structures, but on calculations.

Calculations carried out by Nuremberg's civil engineering department in 1955[14] show the knowledge level at the time for determining the structural behaviour of stone bridges. With the aid of the thrust line technique, the thrust line for the load case of dead weight and single-sided traffic (one main lane only) was shown to lie within the core, and the bridge thus classified as bridge class 30.

Structural calculations for analysis purposes are also part of the current research project. They are based on data verified by the drillings carried out by LGA, both in terms of the geometry and the material properties. They also aim to compare structural calculations from today's viewpoint with the historic techniques for determining the load carrying capacity.

Conclusions

Despite the fact that it is one of the most significant historic bridges of the early modern age, the Fleischbrücke —built between 1595 and 1598— with its flat single arch is nevertheless insufficiently documented. This paper provides insight into the aims and the methodology of the current research project «The Fleischbrücke in Nuremberg» at Potsdam University of Applied Sciences, which is scientifically accompanied by Prof. Dr. W. Lorenz[1] and Prof. Dr. A. Kahlow.[2]

The project includes the topics of construction history, building surveying in cooperation with the «Landesgewerbeanstalt» Nuremberg (LGA), department of historic structures, and the structural analysis and finally the assessment of the quality of this bridge both from a modern angle and within the context of its time. It also involves collating scattered design documents, copies of which are recorded in a digital archive.

As a selected example for the history of construction, the design process is explained by means of designs drawings and reports from different workmen and master builders. Built without static calculations, the Fleischbrücke with its large span yet flat arch has been under the spotlight of engineers since the first half of the 19th century, using different techniques to gain a quantitative understanding of the structure.

Notes

1. Prof. Dr.-Ing. Werner Lorenz, BTU Cottbus, Chair for history of building technology, http://www.tu-cottbus.de/bautechnikgeschichte/index.html
2. Prof. Dr. phil. Andreas Kahlow, FH Potsdam, Department of structural design history, http://www.fh-potsdam.de/~Bauing/personen/lehrende/kahlow.htm
3. http://www.historische-meile.nuernberg.de/englisch/e_start.htm
4. Prof. Dr. Dr. rer. pol. habil. Wolfgang Frhr. Stromer v. Reichenbach.
5. StaatsAN: Stromer archive, B15.
6. e.g. span 15.6 m: Mislin (1997, 300).
7. e.g. Sporhan-Kempel and Stromer (1962, 282); Pechstein (1975, 75).
8. StaatsAN: Stromer archive B15, BMB I, fol. 79.
9. StaatsAN: Stromer archive B15, BMB I, fol. 81.
10. StaatsAN: Ratsverlass Nr.1658, No13 fol. 33/33 verso, 7.4.1596.
11. Equations for the arch thickness depending on the theory see also Falter et al. (2001a, 25; 2001b, 898).
12. GNM: Hs 31700 or transcribed in Pechstein (1975).
13. StaatsAN: Ratsverlass 1686, No 3 fol. 44/45, 8.7.1598.
14. Tiefbauamt Nürnberg: Hauptakte 650–41–01/020.

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The construction of the Potomac aqueduct (1833–1841): Pier construction in deep water conditions

Robert J. Kapsch

Last year, in Georgetown, I came across a book published in 1873 by the U.S. Corps of Engineers and entitled, *Report on the Construction of the Piers of the Aqueduct of the Alexandria Canal across The Potomac River at Georgetown* . . . (Turnbull 1873). I was aware of the structure, a masonry pier structure that carried the wooden superstructure of the Alexandria Canal across the Potomac River, just above Key Bridge, at Georgetown. But the date of the book, 1873, was all wrong. The aqueduct had been constructed some thirty-five years earlier. Why would the Corps of Engineers publish a report of the construction of this aqueduct a third of a century after the fact?

In an introductory page, Brigadier-General and Chief of Engineers A. A. Humphreys answered this question; the report was very helpful for engineers facing deepwater pier construction:

> The reports of the progress of the construction of the piers of the aqueduct of the Alexandria Canal . . . were printed by Congress in 1838 and 1841, with accompanying drawings. They have been called for on several occasions by persons engaged in similar undertakings . . . They are of special interest to the engineer on account of the unusual depth of foundation and the difficulties encountered in establishing them. (Turnbull 1877, 3).

The pier construction of the Potomac Aqueduct of the Alexandria Canal had a unique role in the history of American construction. Captain, later Major, William Turnbull, in charge of building the Potomac Aqueduct, was well aware of the uniqueness of this construction project:

> Experience in founding upon rock, at so great a depth, is very limited in this country, there being but one example, viz. the bridge over the Schuylkill at Philadelphia . . . (Turnbull 1838, 7).

Probably Turnbull was referring to the Market Street Bridge in the above quote where building the bridge's piers posed a greater challenge than building the superstructure (Nelson 1990, 43). Up until 1833, American engineers could pretty much ignore the problem of cofferdams and pier construction through the use of large span structures, such as the Colossus of Philadelphia (Nelson 1990) or through the use of suspension bridges. The coming of the railroad changed that. Wider distances would have to be spanned and greater loads carried. On July 4, 1828, the Baltimore and Ohio Railroad, America's first long distance railroad, began construction. By 1833 it was clearly apparent that numerous railroad bridges across deep crossings would have to be constructed so as to drive railroads into the interior of the American continent. But how?

Turnbull was aware of the difficulty he faced in building this aqueduct:

> No descriptive memoir or drawings of this work (i.e. the Market Street Bridge) ever having been published, nor of the London bridges, (the deepest foundation perhaps in Europe,) the engineers, therefore, had to proceed with the

> greatest caution . . . The cofferdams for the construction of bridges of Neuilly and Orleans, designed by the distinguished Peronnet, were selected as models . . . (Turnbull 1838, 8).

There was English language treatises on cofferdam and pier construction, such as Charles Labelye's account of Westminster Bridge (Labelye 1751) or George Semple's *Treatise* (Semple 1776), but these were not available to Turnbull.

Siting the Potomac Aqueduct of the Alexandria Canal, 1830–1832

By 1828, the Chesapeake and Ohio Canal had initiated construction and its drive to the west. The Chesapeake and Ohio Canal was to be constructed on the Maryland side of the river thus bringing cargoes, primarily grain, into the port city of Georgetown. Alexandria, on the other shore of the Potomac River, would lose out to its commercial rival, Georgetown. To forestall this, the leading citizens of Alexandria developed a plan to build a canal from just north of Georgetown, across the Potomac River and down to Alexandria. See Figure 1. In 1830 the Alexandria Canal Company was formed. Congress appropriated $400,000 toward its construction. (Hahn and Kemp 1992, 19). The Chesapeake and Ohio Canal Company agreed to build the northern abutment for the needed aqueduct. In 1830, chief engineer of the Chesapeake and Ohio Canal, Benjamin Wright, was directed to supervise the survey of a route of the Alexandria

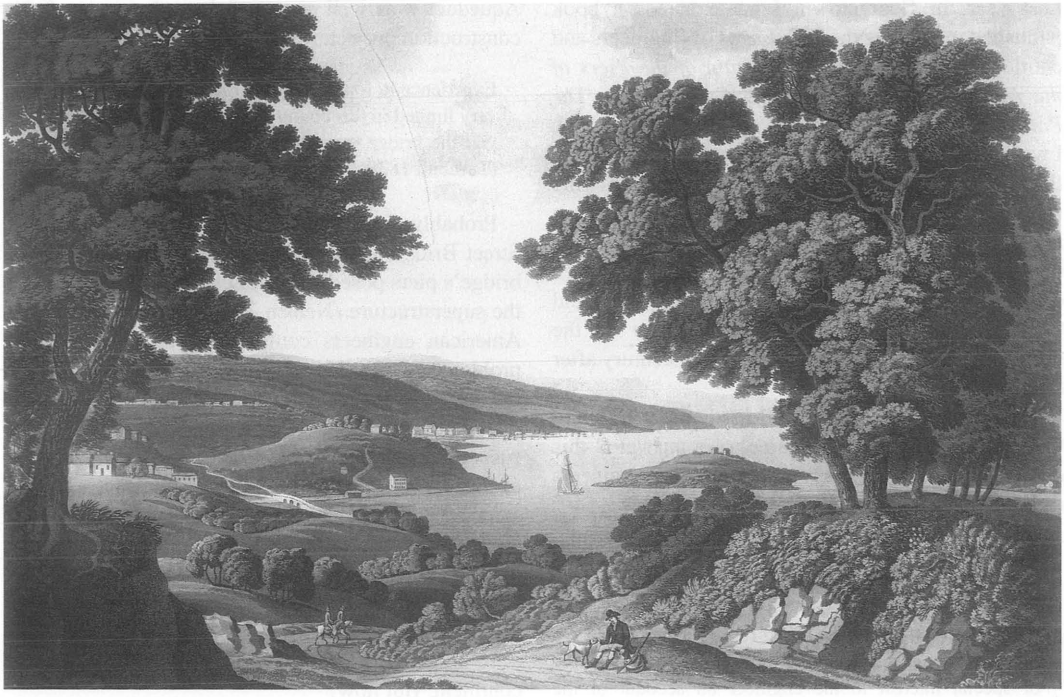


Figure 1
Site of the Potomac Aqueduct crossing. Looking south down the Potomac River. Georgetown is located at the bottom left of this of this early nineteenth century illustration. The new federal city of Washington is located to the middle left. The Potomac Aqueduct would be constructed immediately upstream of Analostan Island, shown here in the middle of the Potomac River. The Virginia shore can be seen, mostly concealed behind the trees, at the extreme right of the image. Georgetown's commercial rival, Alexandria, is seven miles further downriver (south). Drawing by G. Beck, 1801. Library of Congress

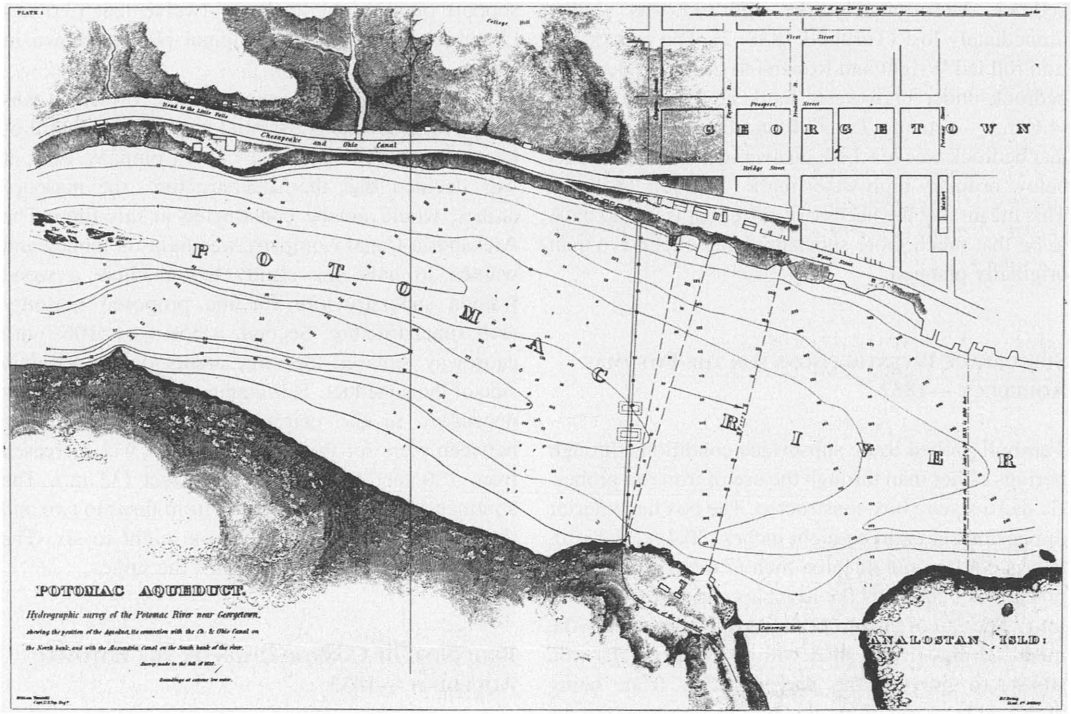


Figure 2
Site plan of Potomac Aqueduct crossing. Site plan of the Potomac Aqueduct. Georgetown and the Chesapeake and Ohio Canal are located in the upper portion of the drawing, Virginia in the lower. The solid, almost vertical line, at right-center of this drawing is the oblique crossing selected by Benjamin Wright and Nathan Roberts. The dotted lines to the right of this solid line indicate the alternate locations selected by Captain William Turnbull. The aqueduct was constructed at the original site. The numbers in the Potomac River indicate river depths. Drawing by Captain William Turnbull and Lieutenant M. C., Ewing. «Hydrographic Map of the Potomac River near Georgetown... Survey made in the fall of 1832.» (Turnbull 1838, Plate 1)

Canal and to take soundings across the Potomac where the aqueduct was to be built (Chesapeake and Ohio Canal Company 1830, entry 182).

Figure 2 shows the site that in 1829 Benjamin Wright and Nathan Roberts selected for the aqueduct. The route is depicted by a solid line from the Georgetown (upper, or northern), shore of the Potomac to the Virginia (lower, or southern) shore of the Potomac. In his official report, Turnbull would criticize Wright for selecting an oblique siting for the aqueduct. Such an oblique siting increased the length of the aqueduct and complicated construction. Turnbull and Alexandria Canal Company engineer W. M. C. Fairfax proposed several alternatives (depicted by dotted lines in Figure 2) which would be of shorter total distance and also bring the aqueduct at right angles with the river flow. These alternative sites were not accepted and the aqueduct was to be constructed on the original site chosen by Wright and Roberts (Turnbull 1838, 3). The total length of the aqueduct on this site would be approximately 1600 feet (487.7 m.).

Turnbull and Fairfax were also critical of Wright's and Robert's attempts to survey the depth of mud in the Potomac River until bedrock could be reached. Wright and Roberts had initiated their survey of underwater conditions by using a 50 foot (15.2 m.) long iron rod for probing the depth of the mud above

bedrock. Unfortunately, the iron rod was almost immediately lost (Turnbull 1838, 2). The loss of the iron rod led Wright and Roberts to guess the depth of bedrock under high-water mark at fifteen five feet (4.6 m.) —actually Turnbull and Fairfax later found that bedrock was reached, on average, 28 feet (8.5 m.) below ordinary high-water mark (Turnbull 1838, 4). This meant that the necessary coffer dams would have to be that much more substantial and expensive than originally planned.

Subsurface Investigations for the Potomac Aqueduct —1832

Turnbull probed these subsurface conditions through borings rather than through the use of iron rod probes. He had a square box constructed. The box had interior dimensions of eight by eight inches (20.3 × 20.3 cm). It was constructed of three inch (7.6 cm) thick heart pine blank banded by flat iron bars and 36 feet (11 m.) long. The end of the box that was to be driven into the mud and gravel was shod with steel tipped flat iron shoes, to prevent the driving edge from being damaged by stones. This box was then driven into the bed of the river from a pile driver mounted on a scow, built for that purpose. It was driven as far into the river bed as could be done without damaging the wooden box. This wooden box was then emptied by means of an auger. Turnbull could thus measure the depth of bedrock at each location, as well as the mud and gravel above that bedrock. The wooden box would then be withdrawn and pile driven into the bed of the river at another location (Turnbull 1838, 3). Through this means, Turnbull was able to draw the profile of the river bed.

Design of the Potomac Aqueduct —1832

Once the profile of the riverbed had been ascertained, the engineers could begin designing the structure of the aqueduct. Initially they designed a masonry aqueduct of twelve arches supported by eleven piers and two abutments. The masonry arches were to be of 100 foot span (30.5 m.) and twenty-five foot rise (7.6 m.). The piers were to be of two types: abutment piers, every third pier (three total), of twenty-one feet (6.4 m.) thickness at the springing of the arch; and support piers (eight total), of twelve feet (3.6 m.) (Turnbull 1838, 4). This original plan is shown in Figure 3.

The original plan for the Potomac Aqueduct was modified in several substantial ways by the Board of Directors of the Alexandria Canal Company. First, it was decided that the superstructure, the masonry arches, would not be constructed at this time. The Alexandria Canal Company was tight on money and wanted to have the ability to substitute a wood framed superstructure for the proposed masonry arch superstructure. Second, a 350 foot (106.7 m.) causeway replaced the three arches on the Virginia side of the aqueduct. This change made other changes necessary in the original design. The distance between piers for the masonry arches was increased from 100 feet (30.5 m.) to 105 feet (32 m.). The abutment piers were decreased from three to two and the support piers decreased from eight to six. The thicknesses of the piers remained the same.

Beginning of Construction on the Potomac Aqueduct —1833

By January, 1833, the Alexandria Canal Company began to make plans for the onset of the 1833 construction season, beginning March 1st. On January 29, 1833 the Company advertised for the construction of the aqueduct. Several offers were received, varying from $99,093 to $247,909. One proposal was received from Doctor John Martineau and Stewart. Martineau had a considerable degree of engineering authority, having served as a Director of the Chesapeake and Ohio Canal —an engineering position second only to the chief engineer, Benjamin Wright.

The First Attempt —Circular Cofferdams —1833

Martineau proposed an innovative means of building the piers, through circular coffer dams. These circular coffer dams would be eighty feet (24.4 m.) in diameter. They would be constructed of two circular rims, one resting on top of each other. These rims were of wooden construction, built from 12 × 14 inch (30.5 × 35.6 cm) mounted vertically in ten foot (3 m.)

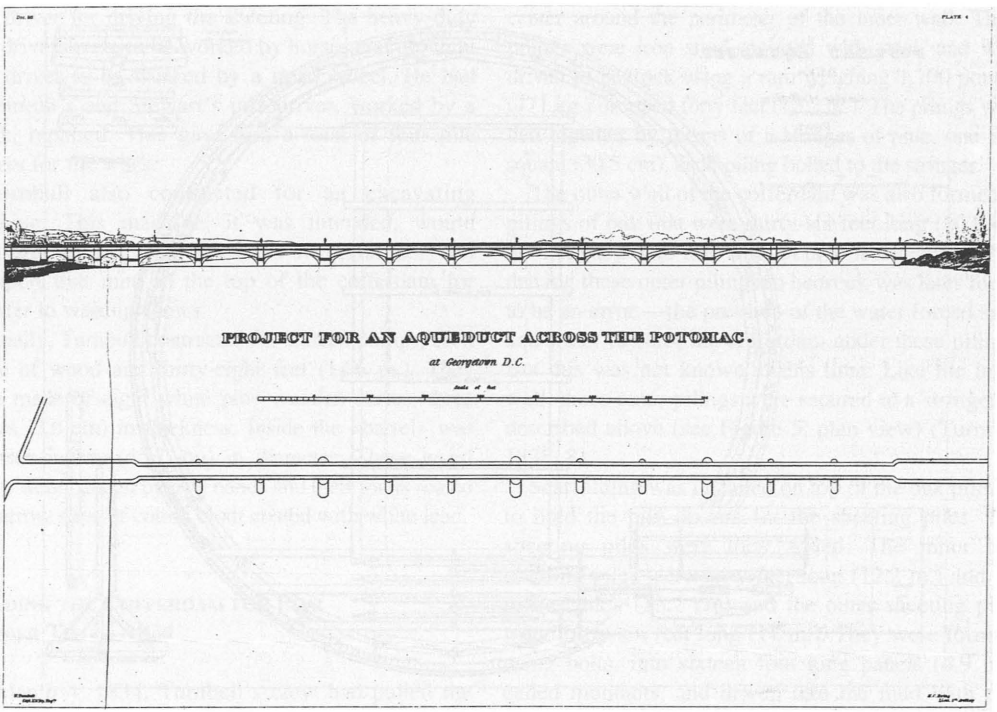


Figure 3
Original design of the Potomac Aqueduct. The Potomac Aqueduct was originally designed as a traditional masonry arch structure of twelve spans. Because of a shortage of funds, the Directors of the Alexandria Canal Company decided on a wooden superstructure instead of the masonry superstructure shown here. The three spans on the Virginia side (right) were deleted in favor of a causeway. Georgetown is shown on the left. Drawing by Captain William Turnbull and Lieutenant M. C. Ewing. «Project for an Aqueduct Across the Potomac.» (Turnbull 1838, Plate 4)

sections and held together with iron dogs. In essence, the circular coffer dam was a single row of vertically mounted beams without cross bracing of any kind. Further, Martineau made no provision to seal this structure through the use of clay puddling or other material. See Figure 4.

Turnbull and the other engineers objected to Martineau's approach for cofferdam construction. But because of Martineau's engineering reputation, the Board of Directors of the Alexandria Canal Company decided to award the contract to him. On June 29, 1833, the Alexandria Canal Company signed a contract with Dr. Martineau to construct the piers and south (Virginia) abutment. The first pier to be constructed was pier number one, adjacent to the Virginia shoreline.

Martineau delayed in proceeding with the contract. It was not until September 2, 1833, that the work for the circular cofferdam was let. By September 26, 1833, the circular frame for the cofferdam was towed into position over the site of the future pier number one. Bad weather intervened. The cofferdam was not weighted down and sunk until October 2, 1833. Only one pile driver was employed and it was not until November 16, 1833 that all the piles had been driven securing the circular cofferdam in place (Turnbull 1838, 6).

The next step was to pump the water out of the cofferdam so construction could proceed. The contractor constructed a platform on piles adjacent to the circular cofferdam but just downstream. On this platform the contractor mounted a 20 horsepower

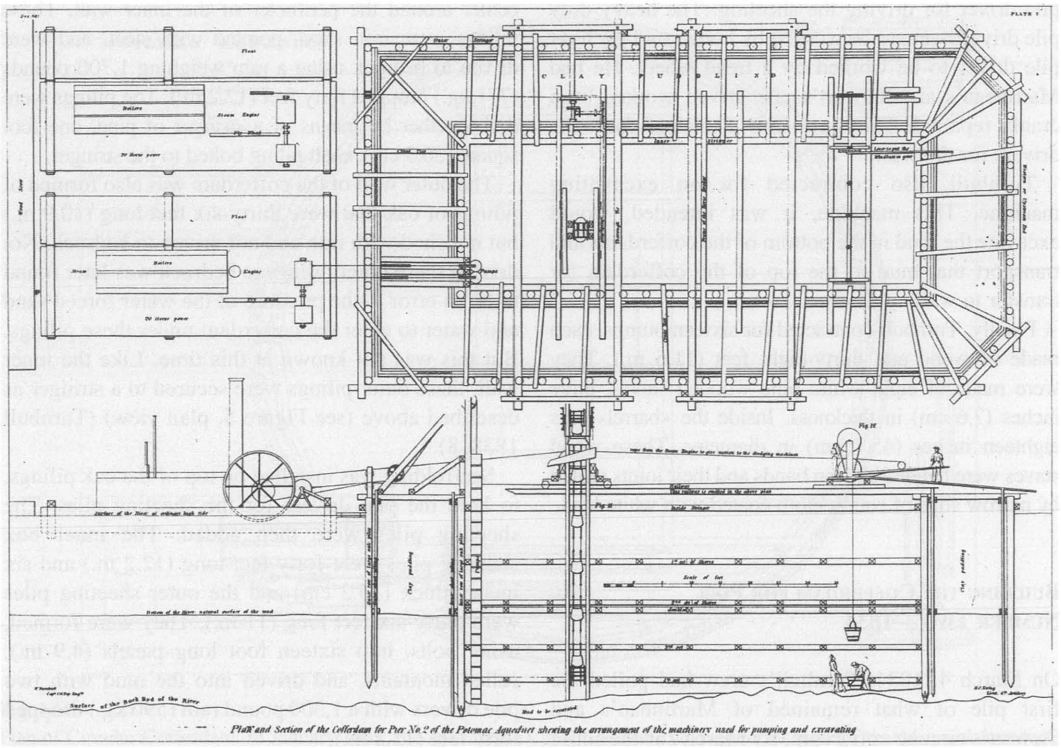


Figure 5
Plan and Section of Turnbull's Cofferdam. In January 1834 Captain William Turnbull took over the construction of the Potomac Aqueduct. He designed a rectilinear cofferdam consisting of a box within a box. Between the outer box and the inner box, Turnbull used tamped puddling as a water sealer. Shown in this plan and section are the scow mounted steam engines used to power the pumps and the excavating machine. Shown in the section are the outer piles which were not driven to bedrock. This later would prove a problem as the water pressure outside the outer box would force water, sand and mud up and under these outer pilings. Drawing by Captain William Turnbull and Lieutenant M. C. Ewing. «Plan and Section of the Cofferdam for Pier No. 2 of the Potomac Aquecut showing the arrangement of the machinery used for pumping and excavating.» (Turnbull 1838, Plate 7)

water so that excavation could commence. Turnbull began the pumps on September 2, 1834 with less than satisfactory results. Ropes stretched and straps broke. Other things went wrong. Turnbull wrote:

> So frequently were accidents happening to the machinery and pump gearing, that the time of pumping in each day rarely exceeded the time noted above (about fifty minutes) (Turnbull 1838, 11).

Slowly Turnbull and his men began to improve the efficiency and reliability of the pumps and the steam engines. The water began to be lowered in the cofferdam. But then it was discovered that the cofferdam structure had to be again strengthened against the outside water pressure. By mid-September 1834, the cofferdam for Pier Number 2 had been entirely emptied of water.

Excavation of the Cofferdam at Pier Number Two —1834

By October 2, 1834, Turnbull was ready to try the excavating machine that he had constructed. The machine, an endless series of buckets driven by a

steam engine in a scow along side the cofferdam, worked well under no load. But when subject to the resistance of the mud to be excavated and the weight of the mud to be carried to the top of the cofferdam, it worked only with great difficulty. Further, to be used as an excavator, it had to be lifted over the shores installed in the cofferdam, a difficult and lengthy proceeding. Turnbull abandoned the idea of using the machine as an excavator and instead used it as an elevator for mud hand dug by laborers. A steam driven windlass, capable of hauling four buckets of 4.6 cubic feet each (0.13 cubic meters), was also used to hoist mud to the top of the cofferdam as was the horse driven pile driver, now converted into a mud hoist machine.

By October 22, 1834, laborers had excavated six feet of mud out of the cofferdam. But then it was discovered that several oak piles on the south side of the cofferdam had failed and that failure had increased pressure on the cross braces at the end which caused them to crack also. While Turnbull was moving to shore up this failure of the cofferdam, a major leak was discovered in the northeast corner of the cofferdam. The pressure of water outside the cofferdam forced the mud under the foot of the outside or «montant» piles which had not been driven to bedrock. The clay puddling soon stopped the leak. After this leak, Turnbull had his men operating the pumps to eliminate the water that had entered the cofferdam. The crank wheel of the steam engine broke halting pumping operations. It was soon replaced.

More troubles plagued construction of Pier Number 2. On November 3, 1834, a large leak developed filling the cofferdam with water. Sand accumulated around the pump in the cofferdam resulting in additional strain on the rope and engine which caused the crank-shaft to break. The engine was repaired and excavation within the cofferdam continued. On November 15, 1835, in the midst of an early winter storm, the workers refused to go to work and stayed off work for several days. The storm caused several of the construction scows to break their moorings and be swept to shore. Leakage continued in the cofferdam and pumping machinery continued to fail, probably because of the extremely cold weather experienced. Despite these setbacks, Turnbull was able to reestablish the stability of he cofferdam and was able to reach bedrock through the mud. Fifteen cubic feet of masonry (0.42 cubic meters) was set in hydraulic cement by the beginning of January. By that time, January 4, 1835, Turnbull had to close down construction operations for the winter and secure the cofferdam and equipment. (Turnbull 1838, 15–18).

Instead of being discouraged by the setbacks of 1834, Turnbull was encouraged that he could prevail. Gradually he and his men had been improving the efficiency and reliability of their equipment. They had learned lessons that would allow more efficient cofferdams for the remaining piers, such as driving the outer pilings to bedrock. Through trial and error they had also learned how to construct a cofferdam that would resist the experienced water pressures.

The 1835 Construction Season

The 1835 construction season started late, in April, due to a delay in securing adequate funds to support construction operations. The first work to be done, beginning on April 22, 1835, was to strip the winter covering off of cofferdam number 2. The pumps were then put back in place, as were the steam engines and the windlasses (needed for hoisting out a small amount mud in the cofferdam).

The immediate need was to implement a system for unloading stones from the scows —stones that weighed from three to four tons each (2722 to 3629 kg.)— lift them to the top of the cofferdam, and then lower them into place in the pier under construction. Lieutenant Bartlett devised such a system for Turnbull. Two railways, consisting of twelve inch square (30.6 cm square) members were placed parallel to each other and securely fastened to the oak piles. On the inner surface of these rails, flat irons were fastened. Carriages were built on top of these. One end of the carriages extended ten feet over the edge, and was reinforced with braces of iron. On top of the carriages were mounted a derrick and on the derrick a winch. The derrick was mounted on wheels allowing travel across the top of the cofferdam. The derricks were operated by four men and a boy. This device thus allowed the derrick to travel over to the edge of the cofferdam, lower a rope to the waiting scow, have a stone of from three to four tons (2722 to 3629 kg.) attached, winch the stone up to the top of the derrick, travel back to the appropriate

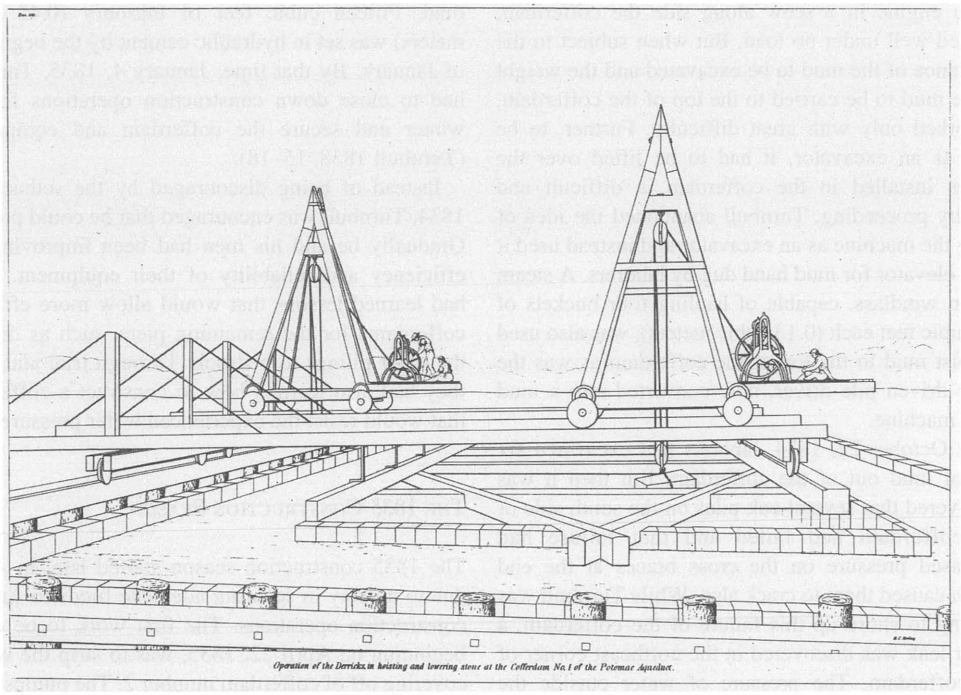


Figure 6
Derricks, Winches and Railway for delivering stone to masons in the Cofferdam. At the beginning of 1835 Turnbull had designed a system to off load three to four tons (2722 to 3629 kg.) stone from scows, lift them vertically to the top of the cofferdam, transport them horizontally across the top of the cofferdam and then lower the stone to the masons working in the cofferdam below. Drawing by Lieutenant M. C. Ewing. «Operation of the Derricks in hoisting and lowering stone at the Cofferdam No. 1 of the Potomac Aqueduct.» (Turnbull, 1838)

position and thus lower the stone to the construction work inside the cofferdam. The two railways, described above, permitted the two derricks to travel longitudinally along the length of the cofferdam. See Figure 6 and Figure 7. (Turnbull 1838, 19).

Special care was taken with the mortar used in the piers. Hydraulic cement was used up to the two foot mark (0.6 m.) above high-water mark, above that common lime mortar was used.

Unlike the excavation work undertaken in the previous year, the masonry work of pier number 2 went quite fast. By June 21, 1835, the masonry of the pier was up to the top of the cofferdam. At this time the derricks and railways, described above, were removed and two booms were installed to assist in constructing the pier to twenty-nine feet (11.1 m.) above high-water. See Figure 8.

With the masonry at the top of cofferdam number 2, it was obvious to all that Turnbull and his engineers had been successful in developing techniques to build piers in deep water conditions. In celebration of this victory, the President of the United States, Andrew Jackson, and his cabinet visited the construction site of pier number two in June 1835 (Turnbull 1838, 20).

Completion of the Potomac Aqueduct —1835 to 1840

Once the techniques of cofferdam construction, pump construction and masonry handling had been worked out on Pier Number 2, construction on the rest of the aqueduct could proceed with few problems. Turnbull wrote of his accomplishment:

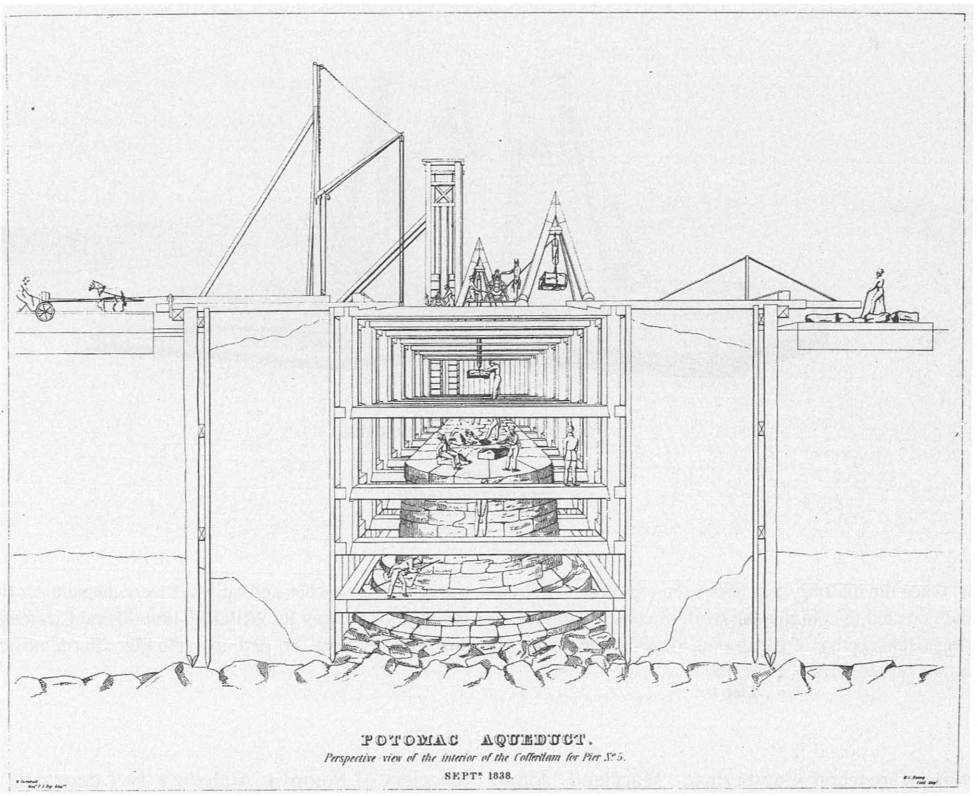


Figure 7
Interior view of pier construction within the Cofferdam. Interior view of the cofferdam showing masonry work and the delivery system of derricks, winches and railway. This perspective was drawn for Pier Number 5. Note that, unlike Pier Number 2, the outer pilings have been driven to bedrock. Also note the dress of the workmen, particularly their top hats. In the early nineteenth century skilled workers frequently dressed well for construction. Drawing by Captain William Turnbull and Lieutenant M. C. Ewing. «Perspective view of the interior of the Cofferdam for Pier No. 5.» (Turnbull, 1838)

> When I reflect upon the numerous difficulties which we have overcome in the progress of the work, and recall the disheartening predictions of that numerous portions of the community who looked upon the attempt to establish foundations at so great a depth, and in a situation so very exposed and dangerous, and who did not fail to treat it as an absurdity, I cannot but congratulate myself upon having so happily succeeded . . . (Turnbull 1841, 35)

Turnbull had constructed one of the longest bridges in America at that time (Mahan 1846, 225). Turnbull had developed a practical approach to pier construction in deep water conditions. This approach was well illustrated by Turnbull and Ewing's drawings and widely distributed through U.S. Government reports. By the time these reports appeared, the American railroad revolution was in full swing and these techniques were used by railroad builders to extend their railroads westward.

Aftermath —The Potomac Aqueduct— 1840 to 2002

In the years 1840–1843, a wooden superstructure was added on top of the masonry piers to carry the Alexandria Aqueduct from the Chesapeake and Ohio Canal in Georgetown to Alexandria, Virginia (See Figure 9 and Figure 10). The Chesapeake and Ohio

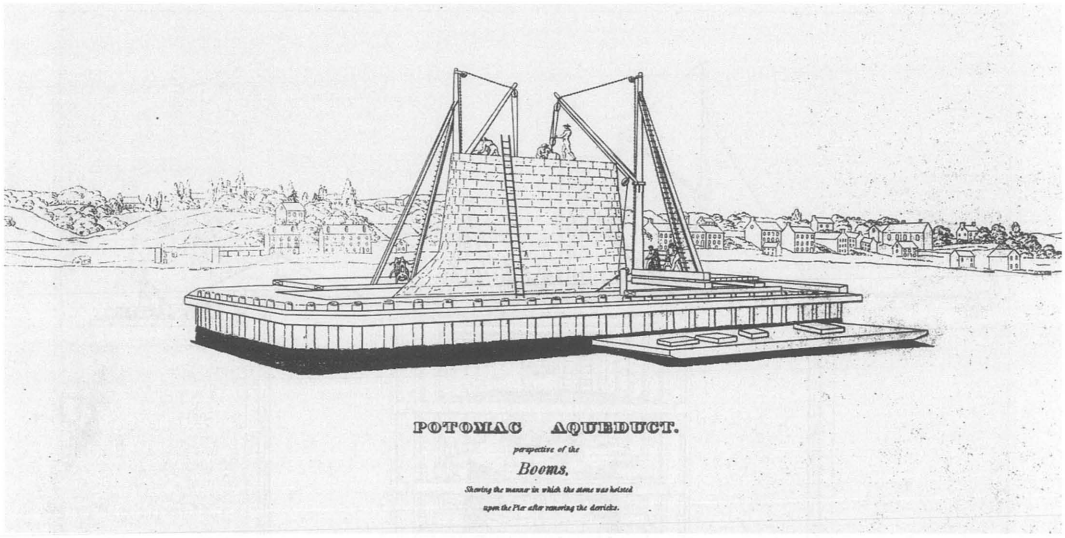


Figure 8
Booms. Once the masonry was above the top of the cofferdam, the derricks, winches and railways were dismantled. Booms were then erected to continue the work of constructing the masonry piers. Drawing by William Turnbull and Lieutenant M. C. Ewing. «Perspective of the Booms Showing the manner in which the stone was hoisted upon the Pier after removing the derricks.» (Turnbull 1838, Plate 15)

Canal itself reached Cumberland, Maryland, some seven years later. Like its larger cousin, the Alexandria Canal saw modest traffic but failed to live up to the expectations of its developers. By its opening in 1843, it was apparent that the future of American transport was with railroads.

With the onset of the Civil War in 1861, the Potomac Aqueduct was drained of water and used as a military vehicular bridge across the Potomac. Following the Civil War, in 1868, the wooden superstructure was replaced by another wooden structure. The new structure was two stories, with road on top and canal on the bottom. In 1888 this second wooden structure was replaced by a metal truss structure that served as a highway bridge. In the early 1920s, the present reinforced concrete arch highway bridge, Key Bridge, was constructed immediately south of the Potomac Aqueduct (Myer 1975). Almost immediately after the opening of Key Bridge, by 1926, the Army was pressing Congress for funds to tear down the old Potomac Aqueduct at a cost of $228,000 (U.S. House, 1926). After World War II the Army received funds to tear down most of the piers of Potomac Aqueduct. Not destroyed were the abutment at the Chesapeake and Ohio Canal, now under the administration of the Chesapeake and Ohio Canal National Historical Park, and a remnant of Pier Number One on the Virginia side.

Summary and Conclusions

What Turnbull had accomplished was pier construction of the Potomac Aqueduct at a deep water crossing. This had been accomplished before in the United States and elsewhere, notably the Market Street Bridge in Philadelphia discussed by Turnbull. But the real significance of Turnbull's accomplishment was the publication of a detailed account, accompanied by the remarkable drawings prepared by him and Lieutenant Ewing, of the construction process of building the piers for the Potomac Aqueduct. This publication came when American engineers were building American railroads westward and faced major river crossings. The report became a manual of construction on how

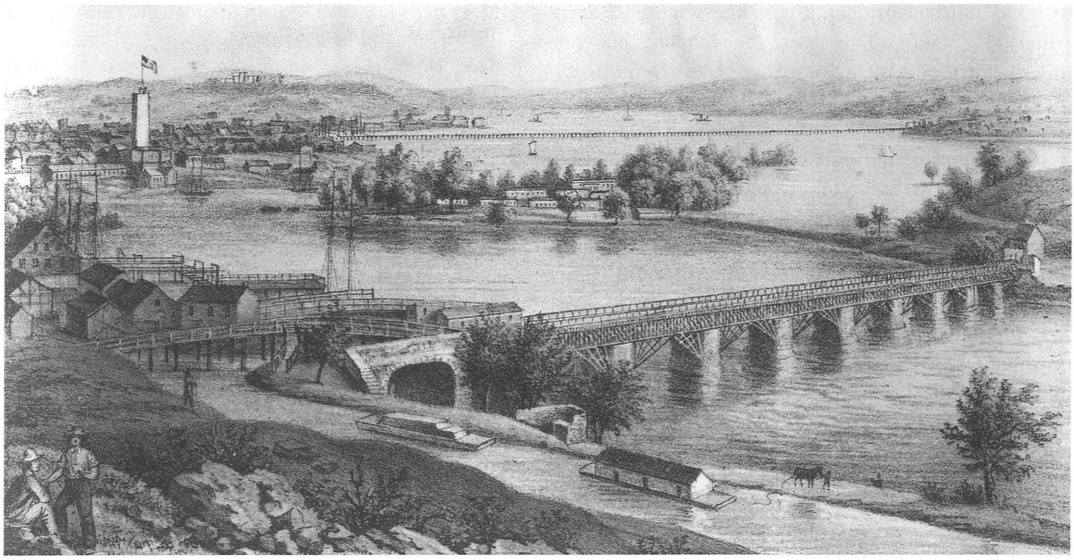


Figure 9
View of completed Aqueduct with wooden superstructure. View of the Potomac Aqueduct from Georgetown, looking south along the Potomac River. The Chesapeake and Ohio Canal can be seen at the bottom of this drawing. The partially completed Washington Monument can be seen on the left side of the drawing. Analostan Island, now called Theodore Roosevelt Island, can be seen in the middle of this drawing. At the time of this photograph the Potomac Aqueduct was dewatered and being used as a military bridge across the Potomac River. Drawing by F. Dielman, 1854. «Aqueduct of Potomac, Georgetown, D.C.»

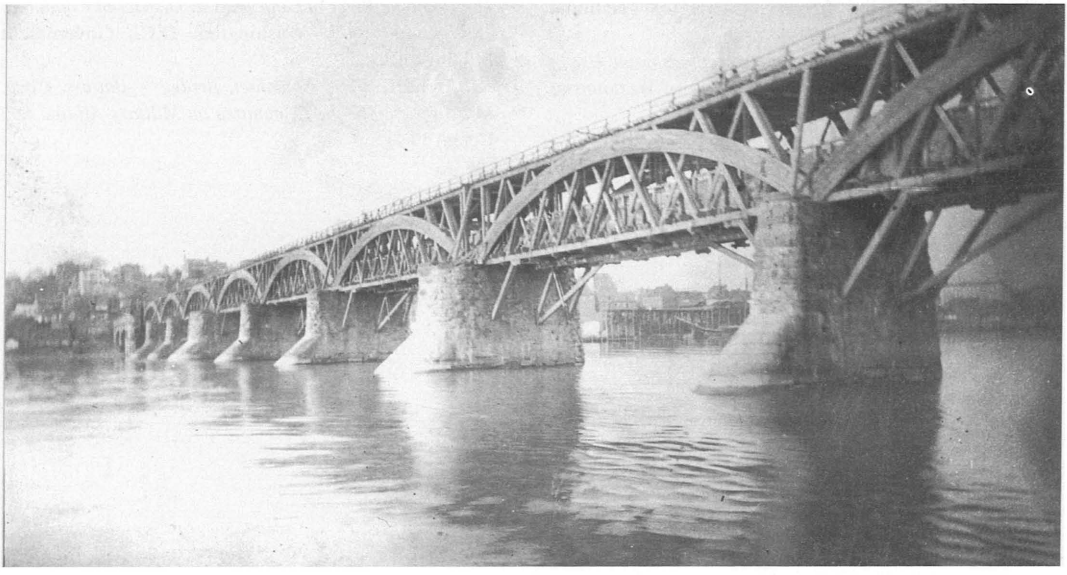


Figure 10
Photographic view of Potomac Aqueduct. View of the Potomac Aquecut, second wooden superstructure in place. Georgetown is behind the aqueduct. Photographed 1868-1877, photographer unknown. Georgetown Public Library

to build railroad bridges across the wide and deep American rivers. This was the reason that his remarkable report was republished by the Department of the Army in 1873 —thirty-five years after completing the construction of these aqueduct piers.

By the end of the nineteenth century, Turnbull's reports would be forgotten. Larger and deeper rivers would have to be crossed. Caisson technology would replace cofferdam techniques. Manufactured iron and steel pumps would replace wooden ones. Structural calculations would replace Turnbull's empiricism. Machine driven pile drivers would replace horse powered pile drivers. Nonetheless, Turnbull's reports of building the Potomac Aqueduct are still of great interest to the historian of construction as the most comprehensive description of an early American engineering construction project.

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The plans and the work-site of Sant'Antonino's chapel in St. Mark's in Florence —the work of Giambologna— in a manuscript in the Salviati Archives

Ewa Karwacka Codini

The manuscript «Notebook of the building of Sant' Antonino's chapel in St. Mark's in Florence, 1579–1589»[1] kept in the Salviati Archives in Pisa,[2] forms a particularly interesting testimony to the planning and realisation of an architectural work in the last two decades of the 16th century in Florence.

The «Notebook» belongs to a kind of writing that is rather rare in the historical archives of noble families and of its kind it is extraordinarily detailed, rich and organic in data. It is divided into two parts: the first contains the journal of the expenses of the period 1579–94, with some copies of bills; the second —the memories of the work by masters and labourers who worked in the chapel from May 1580 to June 1589. Figure 1.

The analysis of the manuscript shows a number of interesting factors about the architect's role in the second half of the 16th century, on the process of joint design , on client's role in conceiving the work, on drawings, plastic works and on yard organization.

The subject of the «Notebook», the chapel of Sant'Antonio in the church of St. Mark's in Florence,[3] commissioned from Giambologna by the Salviati family,[4] is one of the fundamental prototypes of a series of magnificent, celebratory chapels built between the end of the 16th century and the first decades of the 17th, in the Roman area, like those dedicated to Popes Clement VIII, Sixtus V and Paul V in the basilica of Santa Maria Maggiore in Rome. In its composition we find a close link between architecture, sculpture and painting. The chapel, a

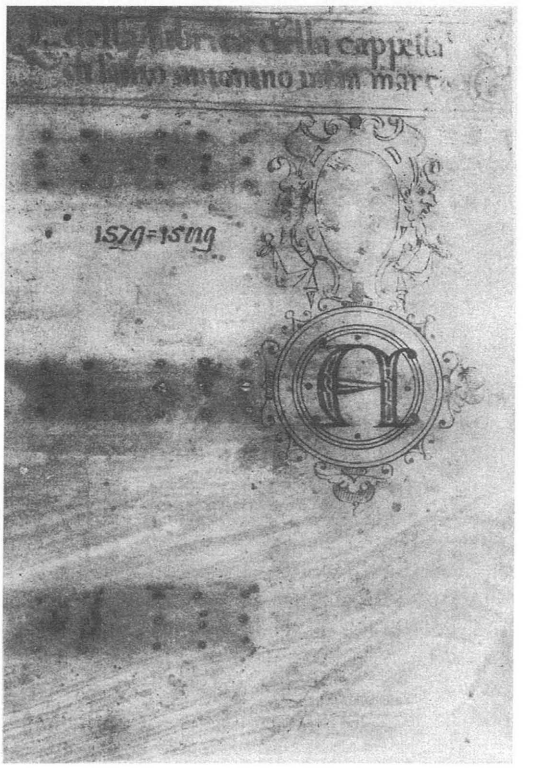


Figure 1
Frontispiece of the*Notebook of the building of Sant'Antonin's chapel in St.Mark's in Florence, 1579–1589* (Archives of Salviati, Libri di commercio e di amministrazione patrimoniale, II, 113)

handsome architectural composition contrasting white and coloured marbles with great dark bronze plaques, assembles the small and rather idiosyncratic repertory of architectural details which recurs in all of Giambologna's architecture. Figure 2.



Figure 2
View of the interior of the Sant'Antonino's chapel, the present situation

The construction of the chapel, devoted to Antonino Pierozzi officially canonized in 1523 by Pope Clement VII, belonged to the renewal counter-reformist program, of the Dominican church of St. Mark.[5] The decisive change of this church (after the elimination of the choir dividing the men's area from the women's) was introduced with the construction of the chapel of Sant'Antonino which stimulated the total change of the interiors.

The chapel is divided into two environments, one at the same level of the central aisle of the church and the other one underground. The upper level is composed of a hallway and of the chapel. Figure 3.

The funeral oratory and the crypt are located underground. Figure 4.

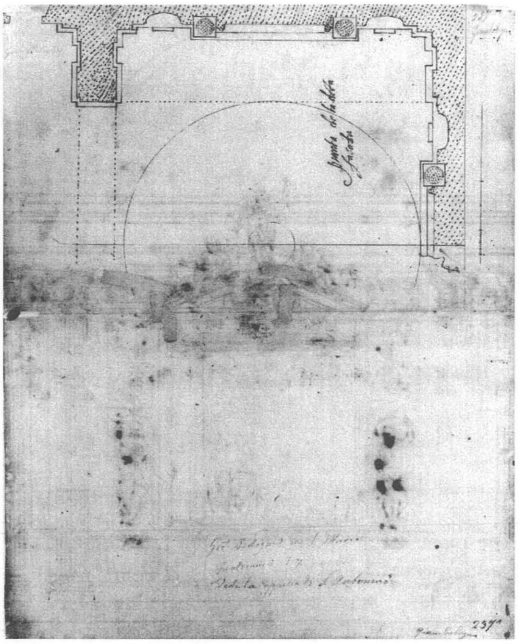


Figure 3
Ferdinando Ruggeri. *Pianta del Vestibolo, e della Cappella di S. Antonino Arcivescovo di Firenze* (Gori 1728)

The entry to the hallway is characterised by a great round arc in serene stone, sustained by composite columns and pilasters, surmounted by the marble statue of Sant'Antonino. In the hallway, the two couples of doors on the side walls are inserted in the frescos of Passignano, *Traslazione del corpo di S. Antonino* on the right-hand side and *Esposizione del corpo di S. Antonino* on the left-hand side. An arc having the same size as the one at the entry toward the central aisle, sustained by two couples of marble pillars in composite style, separates the hallway from the effective chapel. Both inside the hallway and in the adjoining chapel, the architectural body is made of marble. The altar niches in ionic style and other architectural structures are located in the clear grate constituted by a system of composite pillars sustaining the trabeation, applied to niches or panels, elements framing sculptural and pictorial decoration. Under the trabeation each of the three walls is divided into three parts: in the central area we can find the marble altar, whereas marble statues and the bronze

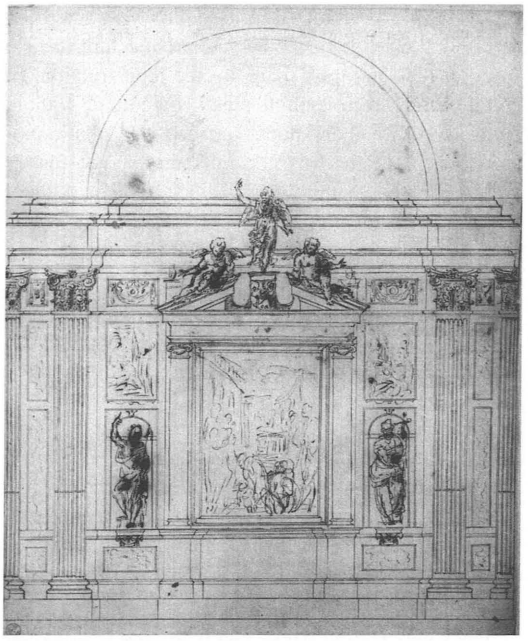


Figure 4
Ferdinando Ruggeri. *Pianta dell'Oratorio sotterraneo* (Gori 1728)

bas-reliefs are located on the sides. On the central altar, Alessandro Allori's canvas with the *Apparizione del Cristo* is accompanied by statues by Saint *Giovanni Battista* and Saint *Filippo Apostolo*. The painting of the *Vocazione da San Marco* by Giovanbattista Naldini is placed near *Saint Domenico* and *Saint Tommaso d'Acquino*, while Francesco Morandini's painting with *Gesù che guarisce il lebbroso* is set near *Sant'Antonino Abate* and *Sant'Edoardo*. Bronze panels above the statues tell the story of Sant'Antonino's life. In the modelling of the walls, characterized by a great plasticity and chromaticity, the architecture is tightly connected to the painting and sculpture. In the middle of the chapel, the sarcophagus of Sant'Antonino rests on a marble pedestal.

The chapel space is sealed by a segment dome with octagonal base, surmounted by a lantern in white marble. The intermediate area with pendentives, the underside of the arches and the dome are entirely decorated with frescos. The pictorial program of the dome is devoted to the *Storie di Sant'Antonio*: four episodes of the Saint's life in the greatest segments and four virtues in the smaller spaces are united by grotesque decoration. Under the arches, the Saint's life stories; on the pendentives and on the sides of the windows —*Prophets and Sybille*. Finally the floor drawing in colored marbles reflects the dome's shape. Figures 5, 6.

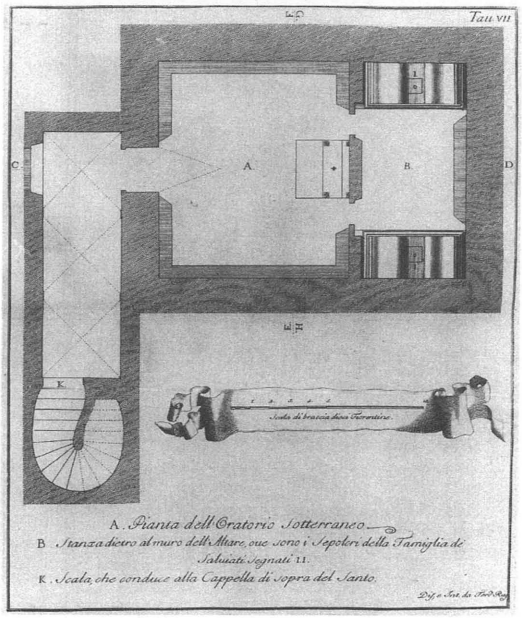


Figure 5
Ferdinando Ruggeri. *Taglio del prospetto principale della Cappella di S. Antonino Arcivescovo di Firenze, e dell'Oratorio sotterraneo, corrispondente alle piante sulla linea C.D.* (Gori 1728)

The clients of the chapel were Averardo (1542–1595) and Antonio Salviati (1554–1619) who fulfilled the last wishes expressed in the will of their father Filippo of Averardo (1513–1572) particularly attached to the Dominican order and great venerator of Sant'Antonino.[6] The construction of the oratory for the family, which had at that time in Florence a notable importance in the economic life and a prestigious political role at the grand-ducal court,[7] was not only a religious fact but also a symbol of munificence and prestige. The work was committed by the family to Giambologna at that time considered as the most

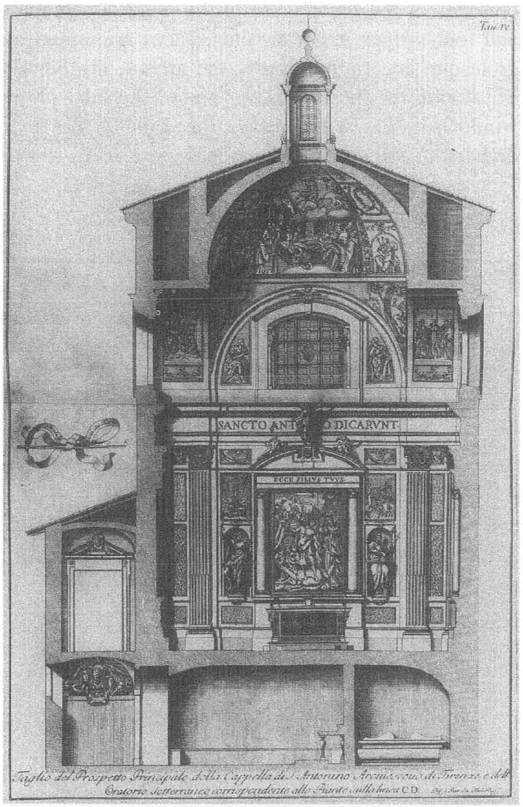


Figure 6
Ferdinando Ruggeri. *Taglio per fianco del Vestibolo, e della Cappella di S. Antonino Arcivescovo di Firenze, e dell'Oratorio sotterraneo, corrispondente alle Piante sulla linea E.F.* (Gori 1728)

famous artist at the grand-ducal court and, as reported by Vasari, «much in grace of our principles for his virtues . . . very rare young man».[8] Francesco I, who employed him exclusively for his works, granted the artist to the Salviati family thanks to the good relationships between the duke and the family. Suffice it to remember on this subject the famous sculptures, realised by him a few years before the assignment, for example the *Oceano* for the Boboli Garden, the *Venus* in the Grotticella, the bronze *Apollo* for Francesco I's private room and the *Rape of the Sabine women* for the Loggia dei Lanzi, initiated in 1579. During his first architectural experiences, Giambologna —like the other sculptors or painters of the 16th century that had been working as architects— used only his trained eye and his knowledge of the ancient architecture. It's no wonder that he took part in the construction of architectural, even though small structures, without being in fact an architect, because the solution of structural problems was generally remitted to master builders and carpenters. After all, according to Alberti, who claimed the prominent role of the ideation and planning in his essay *De re aedificatoria*, the architect shouldn't necessarily be the direct performer of the works, but he had to manage its realisation with intelligence. The first experience of Giambologna in architecture was the *Altare della Libertà* in the church of Lucca (1577–79). Contemporarily to the task entrusted to him by the Salviati family, he was working at the Grimaldi chapel in the church of San Francesco di Castelletto in Genoa (where, after all, he used the same compositive scheme of statues, bas-reliefs, painting and architecture) and since 1584 he had been working at the chapel of the *Soccorso in Santissima Annunziata*, Florence.[9]

The *Quaderno*, in which Giambologna is expressly named «architector», clearly confirms that the architectural ideation of the chapel of Sant'Antonino together with the plastic and figurative creation undoubtedly belong to him.[10] The possible contribution in the planning and realization of artists such as Ammannati, Buontalenti and others, pointed out by some researchers[11] is definitely overcome by the manuscript.

The two surviving drawings of Giambologna for the Salviati chapel, one of the general planimetry and the other of the wall with the main altar[12] do not have the form of a free-hand sketch, which was the most frequent type during the 16th century, but are performed with drawing tools (except for the decorative patterns) and have a metric scale in Florentine *braccio*. Both in orthogonal projections, they are characterised by an extreme descriptive clarity and cleaned lines. The minute and elegant representation of the details is amazing. All the parts of the structure and the decorative body are well defined: not only pillars, columns, capitals, mouldings of the tympanum and frames, but also the entire iconographic program of the sculptures, of the bas-reliefs and of the pictorial panel. With these sketches the design architect transmits the whole and unitary idea precisely defining all the forms, themes and materials. Figures 7, 8.

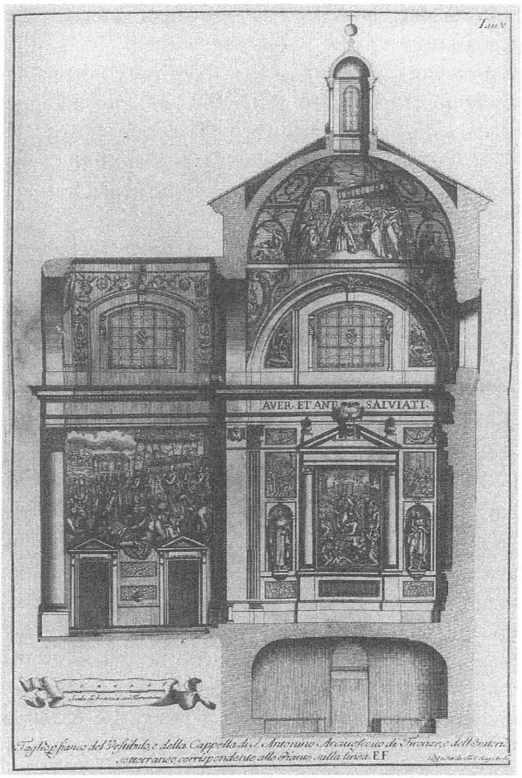


Figure 7
Giambologna. Plan of the Sant'Antonino's chapel (Florence, GDSU, 237a)

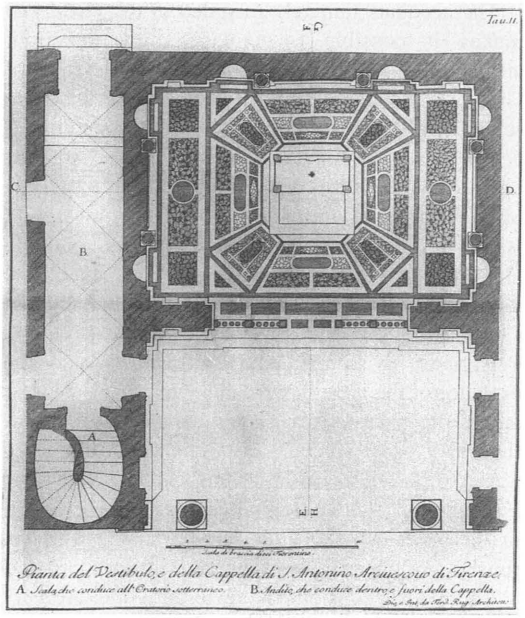


Figure 8
Giambologna. Drawing of the wall with high altar, chapel of Sant'Antonino (Florence, GDSU, 237a)

Considering these particular qualities we can imagine the double finality of these sketches. Undoubtedly they were made to be deciphered by others in the yard. At the same time, considering their communicative completeness, they surely were directed to a cultured client. In fact, we know that some sketches were sent in 1579 in Rome to the archbishop Alessandro de' Medici in order to get his approval.[13] Indeed it was the archbishop who requested the execution of the chapel in the previous years and who then supervised the works with attention.

However, these sketches do not make up the principal means of communication between the architect and the material executors of the works. The transmission of the planner's idea to the workers substantially occurred by using models. The manuscript tells about the great model[14] which, expressing the global original idea, served as a starting point for the realization of single parts, but it also mentions several plastic models of some details in different scales such as the one of the hallway ceiling, of the «dome with eight sides covered with blue cardboards to make the sketch of the paintings», of the windows, of the arcs, of the roof, of the altar, of the cornice and of the sepulchre of Sant'Antonino.[15] The realization of all plastic models was commissioned to the Florentine carpenter Bernardo di Francesco who was qualified for this type of work.

The combination of the arts is the prominent factor also during the realisation of the chapel. The manuscript describing the works includes, in fact, the payments for the architectural parts together with those for the sculptural and pictorial parts, that are considered to be inseparable. The works of architectural decoration interlace and overlap in time with those related to the execution of sculptures and paintings.

The accounts minutely recorded in the *Quaderno* makes it possible to explain some uncertain attributions to the artists. For instance the role of Giambologna as executor of marble and bronze sculptures is explained, this role being ignored by a certain historiography. The manuscript reports the contract signed by the artist and the payments exclusively made out to Giambologna for all the six statues in the niches and for the one of Sant'Antonino above the arc of the hallway.[16] In addition, the plastic ideation of the bas-reliefs in bronze, all made by the Florentine foundry of the Dominican monk Portigiani[17] is confirmed. Portigiani is also the executor of the great winged angel on top of the altar and of the group of two angels lying on the sides of the arc frontispiece, besides the statue of Sant'Antonino for the same altar.[18] Another Florentine smelter, Antonio Susini, was the executor of the oil lamps and grids for the altar and of the finishing of the crucifix of the same altar.[19]

The evidences about the pictorial works are very important as well. as we well know, Alessandro Allori had been chosen for the entire decoration in fresco of the dome, the pendentives and the areas under the arcs, and for the main painting with the *Apparizione di Cristo alla Vergine Maria dopo il ritorno dal Limbo*[20]. The manuscript also reports the payments for the assistants in his workshop, particularly to Giovanmaria Butteri, to Taddeo di Francesco Curradi and Giovanni Balducci. There is evidence of other painters' works: Francesco Morandini and Giovanbattista Naldini[21] for the two paintings of the side altars, and Domenico Passignano for the two great frescos of the hallway.[22] And Simone di Domenico Ferri da Poggibonsi for the paintings of Martini's chapel altar[23] and Lorenzo di Francesco Nelli for the fresco grotesques in the shelter.[24]

The entire manuscript shows the organisation of the yard managed by Giambologna. The role of supervisor and keeper of the *Quaderno* is assigned to Benedetto Gondi, an erudite, expert and collector of Florentine art. He draws up two account books of the above mentioned works organised in two different ways: one is drawn up as a real «diary», and the other reports the payments registered according to their gender and under general expenses. Both manuscripts are extremely precise and full of details in the description of each item. Particularly the first one follows the chronology of the interventions: the preparation of the woks in autumn 1579, the reinforcement of the bases in 1580, the construction of the upper part in the 1582–85 years, the mounting of the dome in August 1585. The four subsequent years were mainly devoted to the introduction of the architectural bodies together with the sculptural and pictorial decoration.

As regards the architectural part, a remarkable role was played by the stonecutter Jacopo Piccardi. It was up to him to choose the marbles in Carrara, to realize some elements and to get them under way.[25] For instance, thanks to the manuscript, we know that he spent one year, in several journeys, in Carrara applying himself to the choice of the marbles.

Piccardi had also to interpret the design produced by the architect and guarantee its realization in the most consistent form. He acts as a foreman: he organises the works, sees about tools and materials and supervises the workers. In fact the realization required to let out several workshops and technicians on contracts. The stonecutters had a major role in the realization of the work as the attendance records show with up to seventy-five workers, while the master masons were only eleven.[26] A long list of other workers is listed, among which carpenters, plasterers, whitewashers, braziers, blacksmiths, panel makers, *tiraferri* (suppliers of copper wire), tinsmiths, *lanciaio* (supplier of iron and copper), locksmiths, receivers, conductors, wheelwrights, «*navicellai*» (conductors of special boats), quarrymen, sawyers, fornacemen, grinders, sand diggers and lustrators.

Among the main supplies listed we obviously find Carrara marble having the major role in the articulation of the interiors. The architectural elements in this material were worked out in the laboratories of Carrara according to the models provided for by the architect. Subsequently they were carried by sea up to Marina di Pisa and from here by the river Arno up to the port of Signa.

The «mixed stones» i.e. the coloured marbles, acquired mainly in Rome, but also in Faenza, Ravenna and Genoa had an important position in the supplies. Giovanni Antonio Dosio, a known expert of Roman antiques and experienced in marble sales is involved in the prospecting and purchase of these stones of archaeological origin in Rome, thereby providing the greatest part of the materials for wall coverings and for the floor.[27] It should be pointed out

that the visual and symbolic meaningfulness of semi-precious stones and the correspondence between the nobility of the subject and the beauty of the shape are confirmed in this period by the Medicean passion for these materials, particularly in Francesco I's interests. However it was Cosimo I who solicited this type of interests after his trip to Rome in 1565, where he had seen the flourishing antiquarian market for their use in the panels, in the wall coverings and in the floors. After his return to Florence he entrusted Giorgio Vasari with the project of a porphyry floor and semi-precious stones and subsequently he entrusted him with the planning, in colored mosaic marbles, of the Chapel of the Principles at San Lorenzo in Florence, wanted by the duke all in colored mosaic marbles.[28] Even though this solution was not immediately realized, this marked the birth of chromatic decorations for private chapels.

The importation from Rome to Florence of the new techniques of marble mosaics starts during the sixties of the 16th century thanks to Dosio who used his experience first in the sketches of panels and then in the planning of the chapel Gaddi in Santa Maria Novella, realized between 1574 and 1578, that is to say immediately before the construction of the chapel of Sant'Antonino. In the last years of the 16th century and in the following century, the predilection for colored and semi-precious stones took the worldly accents in the whole peninsula. The sumptuary use of semi-precious stones replaces with time their symbolic connotation being used in noble chapels.

The success and the diffusion of the chromatic covering in Tuscany is due to the activity of the new Florentine laboratory, specialized in the creation of mosaic and carvings of semi-precious stones.[29] In this laboratory, supervised by Francesco I, Giambologna worked for a long time as one the nine draftsmen. Such experience, undoubtedly affected the ideation of the chapel Salviati, in which he proposed a new solution in Florentine environment playing chromatic effects with the colored stones, sculptures and painting.

In the chapel, Giambologna introduces the coloured stony reflexes in the panels with white architectural structures, combining them with the marble statues placed in the dark grey background of the niches in serene stone, and with the bas-reliefs in bronze and, at the same time, with the pictorial paintings of the altars. He matches the dome frescos with the floor filled with colored stones that reflect the pattern of the dome. A yellow marble column sections, two «African» columns and a piece of green marble, coming from villa d'Adriano in Tivoli,[30] a «white and black» column, two columns of black marble, but also red marble, red and green jaspers and alabaster, all acquired by Dosio in Rome,[31] together with a column of Genovese slate, «mixed stones» from Faenza and Ravenna supplied by Piccardi have been used in the wall coverings and in the floor. This work was very involving when considering the fatiguing and expensive transport on mules. The chapel became famous just for the use of polychrome marbles, as evidenced by Del Riccio in his work *Istoria delle Pietre*[32].

Among the other materials, almost all of local origin, we find: gritstones, strong stones, serene stones, tiles, *mezzane*, *quadrucci* (quadrangular bricks), flat tiles, small tiles, pounded bricks, brick dust and marble, chalk, limes, various metals, as iron, tin-plate, brass, tin, copper and lead, lumber of fir-tree, of chestnut tree and of cypress and glasses.

The contract of these last ones was given to the Ingesuati friars of Florence.[33] For the execution of the windows of the oratory, the ones under the arcs of the vault and the ones under the lantern, the white glass plates coming from Lyon,[34] from Venice[35] and from the same Ingesuati glassworks were used, together with the painted plates from Flanders[36] and the colored glass supplied by the Florentine *bichieraio*, Cesare Bandinucci,[37] as well as the blue and yellow glasses of the same Florentine friars.

The total cost of this «much more regal than civil»[38] chapel appears to be of 34000 scudo[39] (145 scudo per sq. m.). It is a high financial engagement corresponding to the clients' wish for having a grandiose and elegant oratory following the example of the Medicean chapels in Florence. To have an idea of such engagement just compare it with the expense of 12000 scudo for restructuring the Palazzo dei Cavalieri in Pisa realized by Vasari some time before, between 1561 and 1564, upon Cosimo I order.[40]

Great amounts of money, approx. 5700 scudo, are paid for buying construction materials (4000 scudo only for marbles including transport) and approx. 6110 scudo for the stone cutters' work. Giambologna was paid 5400 scudo: 5000 for the sculptural works and 400 for the supervision lasting eight years.[41]

The rather moderate expense, only 1549 scudo, were paid for the paintings, while it surprises the

significant sum of 3023 scudo paid for the hangings of the church of San Marco on the occasion of the ceremony of Sant'Antonino translation which occurred on 8 and 9 May 1589. For the celebration the façades of the chapels, with their pillars, their frames and frontispieces were performed in wood, in line with the Salviati oratorio.[42] This stage pretense constituted in fact the 1:1 scale plan of the architectural transformation of the church occurred within the following decade.

Notes

1. AS, *Libri di commercio e di amministrazione patrimoniale*, II, 113 e 114. The first record was transcribed in 1996, therefore refer to Karwacka Codini and Sbrilli 1996. This record (113) will be from now on referred to as *Quaderno*.
2. It is an important private fund deposited since 1994 at the *Scuola Normale Superiore of Pisa*. Declared of historical interest by the State, these records documents a long period of family story at the end of the 14th century up to the beginning of the 19th century.
3. See Gori 1728 ; Flack 1986 ; Gibbons Weitzel 1995; Centi 1989.
4. For family story refer to Hurtubise, 1985 ; Karwacka Codini and Sbrilli 1987; Pinchera1999.
5. Saint Mark's Dominicans played an important role in defining the new theology of the *Concilio di Trento*. At that time Antonino Pierozzi's thought was recovered by reprinting his doctrinal work *Opera di S. Antonino, arcivescovo fiorentino utilissimo et necessaria per l'istruzione di sacerdoti* (Pierozzi 1559). The first idea for the reconstruction of the chapel was born already in 1526, three years after the Saint's canonization.
6. The relationships between the family and the church and Saint Mark's convent date back to the 15th century. At the beginning of the 16th century Francesco di Bernardo Salviati became the convent's prior: afterwards Filippo di Averardo, who religiously converted thanks to the spiritual influence of the Dominician nun Caterina de'Ricci, ordered the construction of the new church of San Vincenzo in Prato and expressed in the will his desire of building Saint'Antonino's chapel.
7. The Salviati family, already known in the political life at the end of the 13th century, since the end of the 14th became famous for their activity of merchants. Since the half of the 15th century they belonged several counters in Florence, Pisa, Bruges, London and Constantinople. Between the end of the 15th century and the beginning of the 16th century they covered prestigious roles in the political life of Florence. Since the end of the 15th century the family slit up into two branches, the roman and the Florentine one. Jacopo (head of the roman branch) and his sons, thanks to the relationships with the Medici family, and in particular with popes Leone X and Clemente VII, moved a great part of their activities to Roma and in the pontifical state. Alamanno descendants (head of the florentine branch) works during the 16th century in the economic and commercial field and during the 17th century they became landowner and court dignitary.
8. Vasari 1993, 1351.
9. About Sacred sculpture refer to Avery 1987, 193–204 e Gibbons Weitzel 1995. About Grimaldi chapel see Gibbons Weitzel 1984, 278–279; Bury 1982, p.85–128.
10. Refer to Karwacka Codini and Sbrilli, 1996, 135. Payments to Giambologna are reported in the manuscript in due time throughout all construction years.
11. See, for instance, Avery and Radcliffe 1978, card 206.
12. Drawings are kept in Florence at GDSU, (237a).
13. *Quaderno*, c.1v.
14. *Ibid.*, c. 106v, payment to Bernardo di Francesco, carpenter.
15. *Ibid.*, cc. 105(bis), 106r e 106v, copy of an account received by Bernardo di Francesco, carpenter.
16. *Ibid.*, cc. 29r, e 93r.
17. *Ibid.*, cc. 16r e 93r.
18. *Ibid.,* cc. 75v e 93r.
19. *Ibid.,* cc. 81r, 88r, 102r e v.
20. As regards some questions on these attributions refer to Karwacka Codini and Sbrilli 1996, XIX- XX e Lecchini Giovannoni 1991, 271, 312.
21. *Quaderno*, cc.26r e 90r. Naldini is also the author of two fresco paintings of putto in the subterranean chapel.
22. *Ibid.*, c.114r. Frescos *Processione* e *Traslazione* tell episodes of the ceremony dedicated to Saint Antonino on 8 and 9 may 1589.
23. *Ibid.*, c.90r.
24. *Ibid.,* c.82v.
25. Payments to Piccardi are reported in the *Quaderno* throughout the length of the works. As regards marble elements provided for by him, refer to his account a cc. 74v e 75r where, among others, columns, pillars, architraves, frieze, mouldings, fliers, frames of doors and windows are mentioned.
26. See in particular the list of workers' names includine the number of days worked by them: *Quaderno*, cc.145r-325v.
27. Refer to, for instance , to Borsi, Acidini, Mannu Pisani and Morelli 1976 and Morrogh 1985b, 82–85, 88–90, 96–97, 110–111, 112–113,117–118.
28. See in this regards Morrogh 1985a.
29. Refer to Giusti 1989.

30. *Quaderno*, c.91v.
31. *Ibid.*, cc. 25v, 26v.e 43r.
32. Del Riccio (1597) 1979, cc. 3, 6, 10v, 21v, 105v.
33. *Quaderno*, cc.60v e 91r.
34. *Ibid.*, c.89r.
35. *Ibid.*, c.91r.
36. *Ibid.*, c.91r.
37. *Ibid.*, cc.52v e 112v.
38. Bocchi (1591) 1971, 8.
39. AS, *Libri di commercio e di amministrazione patrimoniale*, II, 114, ultima carta.
40. Refer to: Karwacka Codini 1989, 72.
41. *Quaderno*, c.93r.
42. Per la descrizione della festa si veda in particolare Buoninsegni 1589, 3.

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The Wheeling Custom House of 1859: A study in skeletal iron framing

Emory L. Kemp

In the decade before the outbreak of the American Civil War, The United States government built a series of twenty-one custom houses to provide accommodations for the federal custom service, the postal department, and as the location for a federal court (Guthrie 1860, 8).

Although not a coastal location, Wheeling was selected as one of the sites for a custom house, because it was the confluence of three dominant transportation systems: the head of summer navigation on the 981-mile Ohio River, the terminus of America's first trunk-line railway, the Baltimore and Ohio stretching from Baltimore to the Ohio River and reaching Wheeling in 1852, and the coming of the National Road, 1818, which later crossed over the famous Wheeling Suspension Bridges of 1849.

During the fury of the Civil War, the court-room in the Custom House witnessed the formation of a new state on June 20, 1863, to be called West Virginia. The building is noteworthy in the series of custom houses in the Italianate Renaissance style designed by Ammi B. Young, 1798–1874, the first architect of the U.S. Treasury. The construction manager was Captain Alexander Hamilton Bowman, 1803–1865, who was seconded from the U.S. Army to serve the Department of the Treasury. It was Young and Bowman who introduced the use of skeletal iron framing in response to a concern that these custom houses and other federal buildings would be constructed in a fireproof fashion. Fireproofing, in the minds of architects and engineers of the time, was to construct buildings of noncombustible materials. It was not the use of structural iron, a comparatively new material, which compelled Young and Bowman to develop an interior skeletal frame work together with brick jack-arch floors, but to insure the building was fireproof. The focus of this paper, however, is on the evaluation of the structural significance of the iron framing. The effort to achieve a fireproof structure became a criterion for these federal buildings to be constructed of noncombustible materials both inside and out. Thus, in order to understand the decisions made by the Treasury Department, it is necessary to place the design in the context of what was then considered fireproofing ideas.

Fireproof Structures

The concern to construct "fireproof" buildings arose not in the case of monumental public buildings, but rather in textile mills in England. The so called "slow-burn" construction using heavy timber framing and flooring reduced, but did not eliminate, the fire hazard in textile mills, which were illuminated with open flame lighting and devoid of modern sprinkler systems. Although fire protection was a concern in earlier times, the modern period for such buildings dates from the seminal work of William Strutt, 1756–1830, and Charles Woolley Bage, ca. 1752–1822 (Skempton 2002, 28–29 and 670–72).

William Strutt, long associated with the textile industry, and with Richard Arkwright witnessed, in 1781, the destruction of the family mill in Nottingham, England. When Strutt designed a new mill, and later a warehouse, he was keenly aware of the vulnerability of large industrial buildings to fire, especially following the destruction of the well-known Albion Mill in London, which featured innovative production machinery. Strutt's solution was to use flat brick jack-arch floors supported by large timber beams sheathed in iron plates.

Bage in partnership with the Benyon brothers and the flax spinner John Marshall served as designers for a new cotton mill in Derby completed in 1793. The designed called for the use of cast-iron beams instead of the traditional heavy timber girders used by Strutt, Figure 1 (Swailes 1998, 12–19).

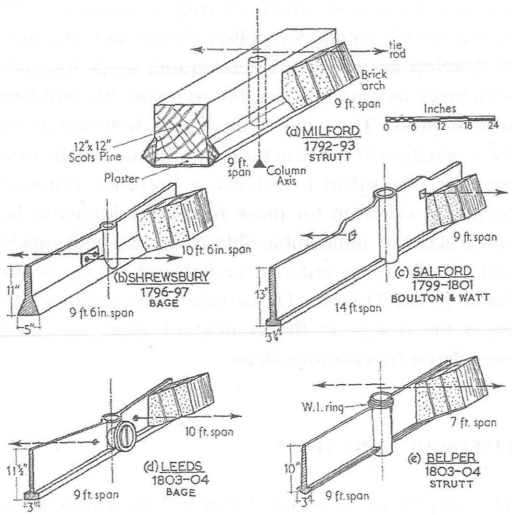


Figure 1
(1958) Evolution of beam design for "fireproof" buildings, 1792–1803 (Singer et al., 477)

The beams of cast-iron supporting 10 foot span brick jack-arch floors are explained by both Swailes and Fitzgerald, Figure 2 (Swailes 1995, 37–47; Fitzgerald 1998, 127–45). The adaptive re-use of such a mill at Huddersfield by Ove Arup and partners considered the load carrying capacity of the cast-iron floor beams supported on a cruciform columns (Robinson and Marsland 1996, 12–13). Such framing systems utilizing cast-iron found widespread use in Britain during the entire first half of the 19th century. While cast-iron beams were largely replaced by mid-century, the use of cast-iron columns persisted into the early decades of the 20th century.

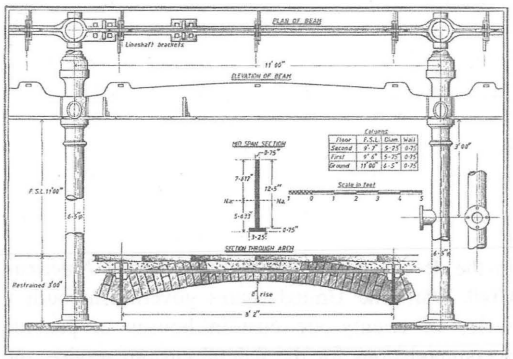


Figure 2
(1998) The Armley Mill, Leeds England (1804–5) featuring cast iron framework and a jack-arch floor system (Swailes, Tom and Joe Marsh, 16)

A notable example of fireproofing occurred across the Atlantic in an attempt by architect Robert Mill's Public Record Office in Charleston, South Carolina. Completed in 1823, the extant structure was erected without benefit of iron framing by using stone columns and walls and brick vaulting (Condit 1960, 26).

Buildings by Daniel Badger and James Bogardus took the process forward by featuring cast iron facades in the years prior to and just following the American Civil War, 1861–1865. Bogardus's Harper and Brothers building was a landmark, a veritable essay in iron. At his New York foundry, Bogardus cast girders and columns for the iron framing. The partitions were brick, and most importantly, the floors consisted of flat brick jack-arches supported on rolled wrought-iron rail-beams supplied by the Trenton Iron Works. It was this firm which played a leading role in the large federal government building program, and especially the Wheeling Custom House. As a result, it

set an important example in the building arts. It should be noted in passing that this was the same period that the great Crystal Palace of 1851 was erected in London. It was so revolutionary, using glass and iron, that architects declared it non-architecture, because it did not use traditional materials. In many ways, it was the most revolutionary and important building of the 19th century. Thus, by mid-century, skeletal iron framing was well established leading to the celebrated sky-scraper.

Recognizing the inherent weakness of cast-iron in tension, the girders supporting the floor system in the Harper and Brothers building were enhanced with wrought-iron tie-rods, Figure 3. Such a system of augmenting the inherent weakness of cast-iron in tension was used earlier in Britain. The wrought-iron floor joists installed were the first 7-inch rail-beam rolled in the United States (Condit 1960, 35–36). Completed in 1854, the Harper building survived until 1920 when it was demolished to be replaced by a newer building.

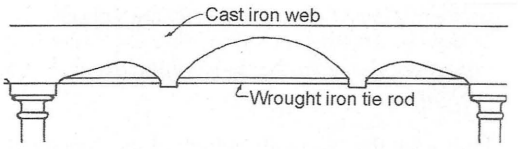


Figure 3.
1960) Composite cast and wrought-iron girder (Condit, 36)

Another memorable building contemporaneous with the Wheeling Custom House was the Cooper Union building under construction from 1854–1859. Founded by Peter Cooper, the Union served as a free school for art and engineering for working class students, both men and women. Again, Trenton Iron Works supplied the wrought-iron joists, their third such project employing rolled wrought-iron members.

The Trenton Iron Works

To many, Peter Cooper's fame rests on his building of the Tom Thumb, a diminutive locomotive for trials on the Baltimore and Ohio, and the subsequent and celebrated race with the grey mare. The Tom Thumb was, in a sense, a plan to secure business for his firm with the Baltimore and Ohio Railroad to supply iron, particularly rails, for this expanding system. Because of the poor grade of iron ore available in the Baltimore area, Cooper decided to sell his Baltimore iron works and relocated in the New York area by acquiring a foundry, which he subsequently upgraded. He pioneered the use of anthracite as the fuel, and also as a powerful reducing agent in the production of pig-iron. It was also used in puddling furnaces to convert pig-iron to wrought-iron. His contribution to the fledgling iron and steel industry included the production of America's wrought-iron "I" cross-section beams. It was his 9-inch "I" beams which were an integral part of the iron framing of the Wheeling Custom House, and a plethora of government buildings under construction at the time.

In an effort to expand his company, he moved again to a location in the Lehigh Valley to have access to anthracite coal and high quality iron ore, both of which could be transported by water, and later by the expanding rail network. For his rolling mill, he relocated to Trenton on the Delaware River. This location was also served by the Delaware and Raritan Canal, and in addition, by railway lines. Phillipsburg, New Jersey, on the Delaware River, was selected for the production of pig-iron since it was close to the raw materials needed.

Peter Cooper planned to establish his son Edward in a managerial position, including product development. Edward responded by suggesting a partnership arrangement with his tutor at Columbia College, Abram S. Hewitt (National Register nomination for the Cooper Union Building). Like partnerships such as Rolls and Royce or Boulton and Watt, the Cooper-Hewitt pair were quite complementary with Hewitt exhibiting a forceful personality, which was essential in the development of the firm, while Cooper, not a decisive decision maker, had highly-developed mechanical skills coupled with an inventive streak. Although the elder Peter Cooper was opposed to the partnership in the beginning, he relented by agreeing to establish the Trenton Iron Company, and a company called Cooper and Hewitt. This latter company served as the manager for the Trenton Iron Company. Both of these organizations were established by 1845.

During the next four years the firm enjoyed a close working relationship with railways, particularly a flourishing market for rails. The economic boom did not last as British firms invaded the home market, and in modern parlance "dumped" rails on the market at half the previous price. The Trenton Iron Works continued to draw wire, which was a hedge against the weak iron rail business, but more important for our concern an interest in the large government public works programs, which necessitated diversification by rolling iron beams for the construction of "fireproof" buildings beginning with the Harper Brothers and Cooper Union buildings.

The first beams resembled railway rails with a bulb top and flat bottom flange. As early as 1847, under the aegis of Peter Cooper, the company attempted to roll 7-inch rail-beams, but was unsuccessful and succeeded in causing the company to invest $30,000 needlessly (Shaw 1960, 18). It was about this time, 1845 and later, that the first "I" beams in Britain were rolled as a substitute for curved cast iron ribs in the monumental Palm House at Kew Gardens near London. (Peterson 1980, 67–70; Peterson 1994, 17–25).

A second attempt to produce a 7-inch bulb rail-beam occurred in 1852 in connection with Peter Cooper's decision to build the Cooper Union building. This deeper member could be employed for main line track by railways, but even more important was sensibly the shallowest beam, which could be employed as floor joists with reasonable spans, which would provide both the strength and stiffness necessary. The success of this second attempt is credited to William Borrow, a recently landed emigrant in 1851 from the British Isles. He designed a new and much more powerful rolling mill. The following quotation paints a vivid picture of iron production at the Trenton Iron Company:

> They consisted of puddling furnaces, heating furnaces, rolling mill, and wire mill, equipped with machinery that was partly American and partly English. The double puddling furnaces, which steadily increased in number until by 1854 there were twenty-two, converted molten pig-iron, under constant stirring by skilled workmen, into wrought iron or at least a better quality of cast iron. The double heating furnaces, of which there were six in the year named, heated the pigs or ingots for the first rolls–those which crushed them into flat blooms or billets. These billets, taken up white-hot, were then shot forward through a series of other rolls adjusted to turn them into rails, beams, or roods, as desired. As the smaller pieces went forward, hissing whenever they touched any moisture, they rapidly took on the aspect of fiery writhing snakes, struggling in the murky gloom to escape workmen who caught them with pincers and thrust them back and forth with incredible quickness. When the larger rails were ready for final shaping, vises seized them and laborers hammered away deafeningly. As they finished, the rail was pushed under sharp steel saws which cut it to the precise length required. It then passed to a cooling-bed, and when quite cold was thrust into powerful presses, which straightened out bends or other irregularities. There were also foundries and pattern-shops for the production of special casings, and blacksmith shops and machine shops. "No pains or expense have been spared," Hewitt wrote in 1854, "to make the mill perfect in its arrangements."
>
> Power was derived partly from the race of the Trenton Waterpower Company, with three great wheels serving the mills, and partly from steam, for two engines were operated by the waste heat of the furnaces. Anthracite was of course used at both Phillipsburg and Trenton. The whole plant had a capacity by 1854 of more than 35,000 tons of finished iron annually–a spoonful to the gargantuan production of after years, for Hewitt lived to see a single American corporation formed with an annual capacity of 8,000,000 tons of finished steel; but a very satisfactory figure in the early fifties (Nevins 1935, 99–100).

Following the successful rolling of the 7-inch rail-beam, the firm advertised with a broadside featuring the use of their wrought-iron 7-inch rail-beams supported by wrought-iron box girders composed of iron plates, riveted top and bottom with rolled iron channels. This was the system proposed for the Wheeling Custom House, 1856–1859.

The two plants produced the 7-inch rail-beams. The first consisted of three tall blast furnaces at Phillipsburg using New Jersey ore, and some from Pennsylvania, together with anthracite to produce pig-iron, the annual production amounted to more than 25,000 tons. The pig-iron was shipped by water and rail to Trenton.

The Trenton mill consisted of twenty-two double puddling furnaces for converting pig-iron to wrought-iron by reducing the carbon content to nearly zero. The result was wrought-iron as described above. There were six double heading furnaces for heating the wrought-iron so that it could be rolled into billets. The white-hot billets were then rolled into rails,

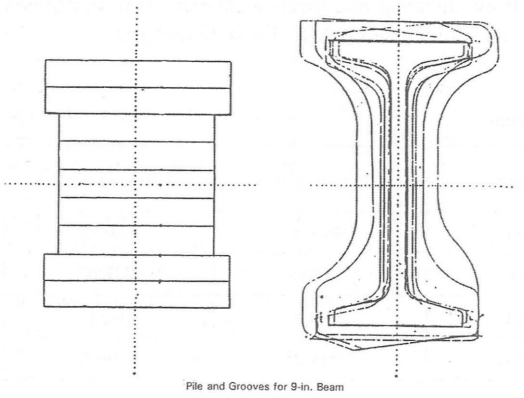


Figure 4
(1998) Transformation of a wrought-iron pile into an "I" section by repeated rolling of hot wrought-iron from Weissenborn 1861 (Elban et al., 38)

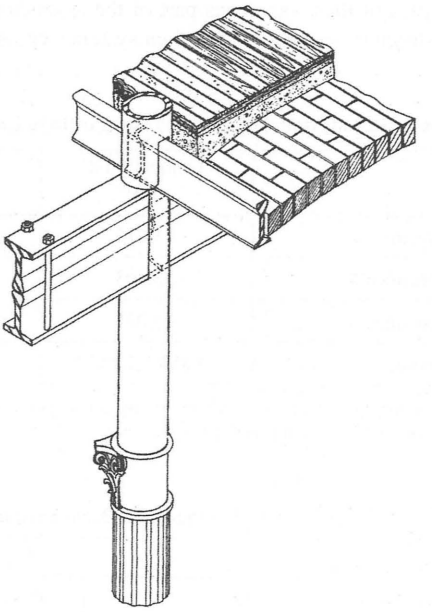


Figure 5
(1980) Detail of the skeletal framing used in the Cooper Union building (Peterson, 18)

beams, angles, channels, and other shapes depending upon the configuration of the rolls. Since the puddling furnaces were unable to produce enough wrought iron to roll a beam, a pile composed of wrought- iron bars was stacked up, heated, and rolled producing a symmetrical "I" beam, which was noticeably more efficient in bending than a rail-beam with a bulb top, but proved to be a difficult proposition to roll since one set of rollers had to fit between the flanges, Figure 4 (Nevins 1935, 116–17).

With the success of the Harper Brothers building and the work on the Cooper Union building, Figure 5, Young and Bowman decided to use wrought-iron rail-beams in the federal government Assay Office in New York. The required number of beams were rolled, which held up work on the Cooper Union building, but by the end of 1856, the Union building was nearly complete. With the success of these buildings, the Treasury Department adopted the Trenton iron beams and box girders for all of its public buildings.

Although William Borrow, the mill superintendent, installed new heavy machinery, the struggle to produce a 7-inch rail-beam was a costly endeavor amounting to a debt of $150,000 by the company. It, nevertheless, was a success. Borrow's new mill successfully rolled the rail-beam in the spring of 1854, but he died on October 1 of that year before he could undertake to produce a true "I" beam as a replacement for the bulb-tee section. This task was left to Charles Hewitt who modified the rolls to produce an "I" beam with symmetrical flanges. Shortly after Borrow's death and not later than the spring of 1855, the first 8-inch "I" beam was rolled (Shaw 1960, 20). By any evaluation it was a major accomplishment worthy of celebrating, but alas remembered by very few. During the next year, 9-inch "I" beams were delivered to the Wheeling, Virginia (later West Virginia) Custom House, Figure 4 (Shaw 1960, 31; Nevins 1935, 174; Jewett 1969, 390–91).

Wheeling Custom House Beams

The floor joists used throughout the Wheeling Custom House are amongst the earliest "I" beams in existence, having been supplied in 1856 as noted above. During the recent restoration, wrought-iron

samples of these beams as part of the assessment of the structural capacity of the floor system were tested. Both chemical and mechanical tests were performed and summarized below, Table 1a and 1b:

Table 1a Results from Destructive Testing of 1856 Iron Specimens

	Young's Mod. (ksi)	Yield Stress	Ultimate Stress	Ultimate Strain
Specimen 1	23,025	34 ksi	48 ksi	0.095
Specimen 2	23,803	42 ksi	48 ksi	0.0087
Specimen 3	25,021	39 ksi	54 ksi	0.11
Average	23,950 (23,743)*	38.3 ksi	50 ksi	0.0712

*The values in parentheses include the results from a static compression test.
N.B. ksi = one thousand pounds per square inch.

Table 1b Composition of Wrought-Iron-Beam Sample From U.S. Custom House, Wheeling, West Virginia, percent.

	C	Mn	P	S	Si	Slag
Beam Sample	<0.005	0.029	0.610	0.039	0.590	7.4*
Typical hand-puddled wrought iron**	0.06	0.045	0.068	0.009	0.101	1.97

*Weight Percentage based on a volume percentage of 12.5 measured with the quantitative television microscope and assumed specific gravities of 4.5 for slag and 7.6 for wrought iron.
**For wrought iron made before 1930. Reference: Metals Handbook, 1948 Edition, page 504, American Society for Metals, Cleveland, Ohio. Tests by United States Steel Corporation, Pittsburgh.

Three tension tests revealed typical values for wrought-iron showing considerable ductility and strength. Sample one, however, failed in the fillet zone as did sample two where a large slag inclusion was present. The third sample failed in a ductile manner and exhibited the highest ultimate stress, Table 1. Earlier the results of a chemical investigation revealed important information on the wrought-iron used in the Custom House. It was found that both phosphorus and sulphur are an order of magnitude higher than traditional values. While the phosphorus adds fluidity to the molten iron, both phosphorus and sulphur embrittle the iron after cooling.

The method of production greatly influences the final behavior of the wrought-iron. It was not possible with the puddling furnaces available to produce a bloom of sufficient size to roll a 9-inch section 20-feet long. The solution employed was for a pile of wrought iron bars to be stacked, heated, and rolled. With sufficient temperature, the successive rolling would weld all of the bars together and produce a final "I" section. In cooperation with Loyola College, a metallurgical assessment of the 9-inch wrought-iron beams was undertaken (Elban 1998, 27–35). The results were published, and the conclusions gave an admonition for those dealing with historic wrought-iron structures that there are wide variations in physical properties. It is necessary for those involved in assessing and / or restoring early wrought-iron structures to deal with this material on a case-by-case basis. The inclusion of large amounts of phosphorus and / or sulphur will significantly reduce the fatigue capacity of wrought-iron.

Equally important, the system of rolling structural sections from a pile of bars can produce well-defined boundaries between the bars if the rolling temperature is below white heat. This is the case in both the bottom and top flanges of the sections tested from the Custom House. This has not, however, resulted in a reduction of flexural capacity, but could lead to

delamination under certain loading condition such as the application of repeated loads.

The box girders riveted out of wrought-iron plate and channels support the 9-inch joists. Both the plate and the small channels were much easier sections to roll compared to the 9-inch "I" beams. While the box girders supported the floor joists, they were, in turn, carried at each of the three floors by cast-iron columns. These columns, and indeed all the cast-iron work in the Custom House, represents the handiwork of local foundries. Wheeling was, after all, a leading iron producing center suppling iron products for the boat building enterprise, the nation's leading center for the production of cut nails, steam engine production, together with wire manufacturing (Davis, [1861] 1972).

Having made the decision to use the Cooper & Hewitt iron framing system, a flourishing correspondence ensued, beginning in 1854 between the company and the U.S. Treasury Department, Figure 6. In these early letters, the concern was the utilization of the 7.25-inch iron rail-beams. In the original design of the Wheeling Custom House these beams were featured. The rail-beam members were tested in various configurations in an effort to enhance the strength and stiffness of the basic rail-beam. P.G. Washington, writing on behalf of James Guthrie, the Secretary of the Treasury, issued orders to Lieutenant G.B. Alexander which say in part:

> From Philadelphia you will proceed to Trenton, N.J. where experiments are in readiness to test the strength of wrought iron beams and girders which I wish you to witness and report the results with as little delay as possible as very large orders are about being given for both beams and girders which may have to be modified if the results should disappoint expectations (NARA, RG77, Dec. 9, 1854).

On the same day, the Secretary wrote to Cooper & Hewitt in New York City concerning the wrought-iron box girders.

> To: Cooper & Hewitt, New York City
> Dec. 9 1854
> Gentlemen:
> In relative to the thickness of the plate iron for the girders it will to a great extent depend on the length of the girder and on the strength of the form of beam as determined by the experiments now making at your mill. The beams in all cases are to be of your largest size pattern. The plan of making a girder by the union of two beams will not I think be practicable, as it would limit constructors to such sizes as two of your present patterns would produce, whereas various sizes would be required.
> P.G. Washington for the Sec. of the T (NARA, RG77, Dec. 9, 1854).

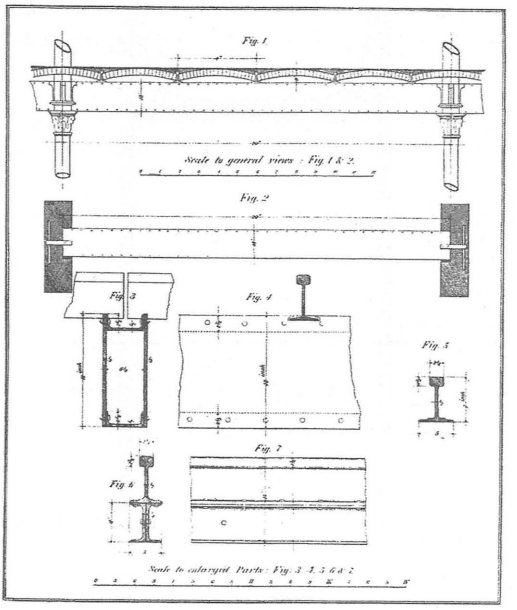


Figure 6
(1980) A Cooper & Hewitt broadside depicting their iron framing system (Peterson, 85)

In a letter to Robert Anderson, U.S. inspecting agent at Trenton, New Jersey, the Secretary authorized the purchase of a testing machine and assigned Anderson to oversee the testing when the testing machine arrived, Figures 7, 8, and 9.

> With regard to the purchase of a machine for testing the beams, I have to state that when Mr. Cooper was here he said that one could be procured for the sum of five hundred dollars. He will be written to today to purchase one, or to have one made as soon as possible. When it shall have reached you, it will be your duty to test each beam and to append a certificate of your having done so to the account of the beams sent in for payment (NARA, RG77, Jan. 25, 1856).

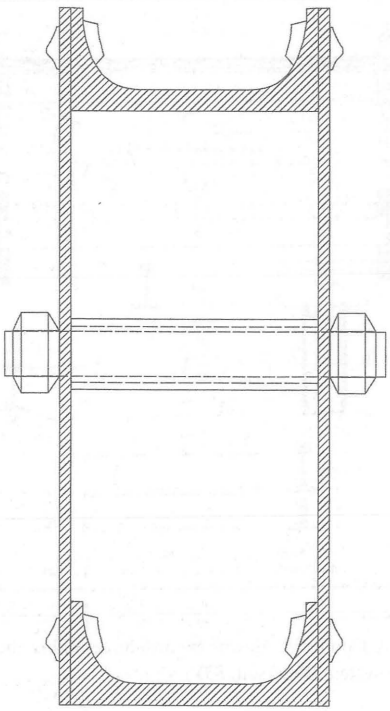


Figure 7
(1855) Iron box girder tested by the Treasury Department (Alexander, 3–5)

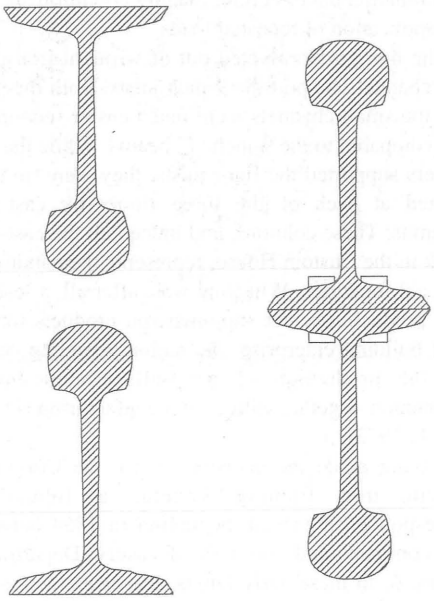


Figure 8
(1855) Various configurations of rail-beams (Alexander, 3–5)

By mid-summer, the Secretary wished to know the "state" of the girders and beams for the Wheeling Custom House.

> You will please inform the Department of the State of the girders I beams for the Wheeling VA, C.H. and whether you have had the necessary drawings furnished you in filliy them (NARA, RG77, July 19, 1856).

The year 1856 saw the request for bids to construct the Custom House. The official record is somewhat confusing. James Milligan, of Pittsburgh, submitted what appeared to be the low bid of $77,920 with the understanding that the Treasury Department would purchase the ironwork directly from Cooper & Hewitt (NARA, RG77, March 19,1856). Several of Wheeling's well known firms submitted bids amongst them, Sweeney with a total bid of $84,431.69, while James Bodley, well known producer or iron wire, bid $9,002.32 for brickwork. Presumably the brickwork was for the jack-arch floors. Many other firm submitted bids, all higher than James Milligan's quote (NARA, RG77, April 12, 1856; NARA, RG77, May 8, 1856). In March 1856, Captain Bowman wrote to James Guthrie regarding the bids submitted suggesting that the bids lacked sufficient details and the job should be rebid. After receiving a second round of bids, Bowman recommended the contract be awarded to William & J. Steward and Philip Schele & Company in the amount of $80,159.97 (NARA, RG77, March 5, 1856; NARA, RG77, June 2, 1856).

The project superintendent, James Luke, informed Secretary Guthrie on July 14, 1856, that the work had commenced and the excavation almost complete. Later, on October 1, 1856, superintendent Luke informed Secretary Guthrie that the beams and girders for the first floor would be shipped from Trenton on or about October 9 (NARA, RG77, July 14, 1856).

Historians welcome logistical complications which generate much paperwork. Cooper, Hewitt, &

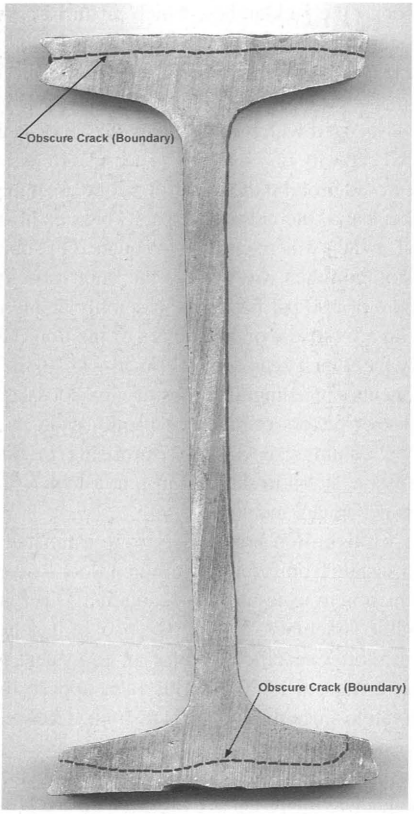


Figure 9
(2002) Cross-section of a 9-inch "I" beam from Wheeling Custom House (Photographed by E. L. Kemp)

Company writing to the Secretary Cobb, the replacement for James Guthrie, explaining the delay in submitting an invoice for the beams made October 28, 1856, arising from the fact that the 9-inch beams were mistaken for the 7-inch rail-beams, which were sent to the branch mint in New Orleans. Since the invoices were also misdirected, it required a reissuing of invoices and appropriate credit given to any payments already made. The story ends happily, however, with the 9-inch beams arriving in Wheeling with white lettering saying Wheeling, Virginia (NARA, RG77, June 5, 1857). Although the building was expected to be completed in 1858, it was in fact a year later that the facilities were opened to the public. Nevertheless, little difficulty was experienced in the construction.

Wheeling Custom House, 1859

The three story building in the Italian Renaissance Palace style measures 85 x 60 feet. The interior columns follow the Greek Doric style in the basement and Corinthian elsewhere, Figure 10. These hollow columns conducted heat to the various floors to provide background heat in each room. Coal fired furnaces supplied the heat from the basement to the various floors. Fireplaces throughout the building supplemented this early central heating system.

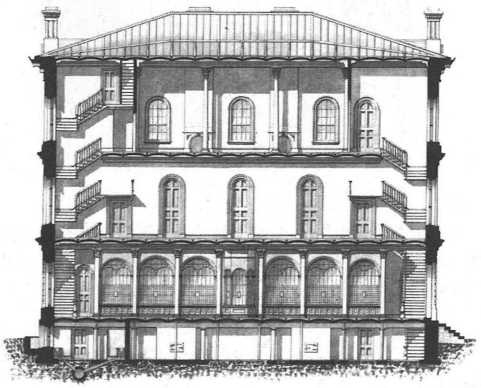


Figure 10.
(ca. 1856) Drawing by Ammi B. Young showing a section through Wheeling Custom House showing the Cooper & Hewitt framing system using 7-inch rail-beams which were replace by the 9-inch "I" beams actually used. (U.S. Treasury Archives, Washington, D.C.)

Beginning at the roof, rail-beams of the 7-inch variety were supplied to support the corrugated metal roofing intended to replicate Italian terra cotta tiles, Figure 11. The only wood in the building was the long leaf southern pine flooring. This wearing surface was secured to wood sleepers imbedded in a light weight concrete matrix used as a leveling course on top of the brick jack-arches. The jack-arches span approximately 5 feet between the 9-inch beams. In the rooms off the corridor, the span is 20 feet whereas the corridor spans are only 15 feet, Figure 12.

In the beginning of the restoration work, in the 1970s, there was an urgent need to establish a safe load capacity for each floor. The initial analysis assumed the load path for the dead and life loads, which passed from

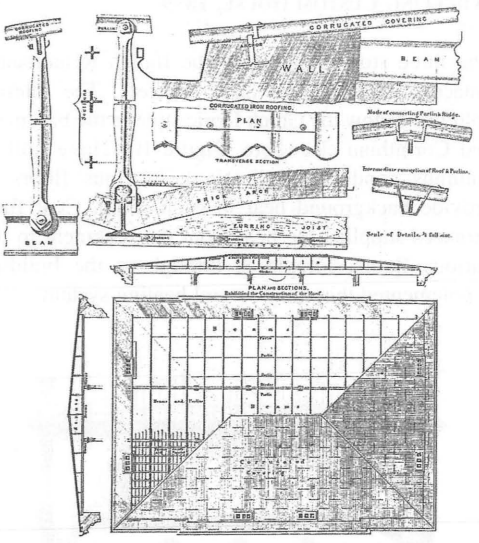


Figure 11
(ca. 1856) Drawing by Ammi B. Young showing the roof iron framing system utilizing 7-inch rail-beams (U.S. Treasury Archives, Washington, D.C.)

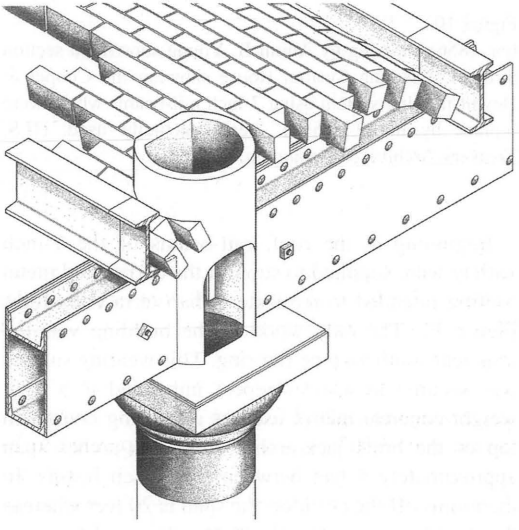


Figure 12
(2002) Drawing by Paul Boxley of the Wheeling Custom House iron framing system (Institute for the History of Technology and Industrial Archaeology Archives, Morgantown, WV, USA)

the floor to the jack-arches, which in turn transferred their loads to the 9-inch "I" beams. This meant that the floor capacity was beholden to the flexural capacity of the 9-inch beams. This study, Table 2, found all the floors associated with rooms having a 20 foot span had a limited capacity of 74.4 pounds per square foot (psf), which would prohibit their use for public assembly. On the other hand, the corridor capacity was estimated at 184 psf, which was more than adequate. One object of the restoration then was to raise the floor capacity to a minimum of 100 psf for public assembly in any room, based on a more elaborate analysis of the floor system. Clearly the 9-inch beams were critical with all the other components exceeding the necessary live load capacity. With larger factors of safety, typically eight used for cast-iron columns, it was not surprising to find the compressive stress in the cast iron at a low 1,100,000 pounds per square inch (psi).

The wrought-iron box girders were estimated to be able to sustain a uniformly distributed floor load of 114 psf, which is in excess of the required 100 psf needed for public assembly. In the absence of test results, modern mortar specifications for an equivalent mortar indicate a value of 1,800 psi. This value appears to quite conservative since the mortar is restrained between the bricks and appears to be of a high quality as a result of extensive examination of the exposed jack-arch floors. This value was then used in evaluating the load carrying capacity of the floor system.

This analysis of the floor system appears to be the correct for the dead loads involved because of the construction method. Although not explicitly stated, it appears that the jack-arch floors were built in the following manner. First, 9-inch beams were placed on the box girders and exterior walls at a nominal spacing of 5 feet throughout the length of the building. The top flanges of the beams were linked at several locations with transfer straps hooked over the flange. These extended from beam to beam throughout the length of the building in an effort to prevent the thrust from the brick jack-arches from overturning the beams, since the jack-arches were build one at a time beginning at one end of the building. It should be noted that the floor joists simply rest on the box girders without any connection to prevent overturning. When the entire floor system was complete, the thrusts on each side of the joists compensated each other, and provide a significant clamping action against the beam webs. Centering for the brickwork was supported on the

Table 2 Summary of Preliminary Structural Analysis

Load Factors (no resistance factors applied):	1.9 Dead Load, 2.3 Live Load
Dead Load:	400 lb/ft of length
Ultimate Strength (assumed):	35 ksi k=1000 lb
Iron I-beams:	
Moment of Inertia (I):	125 in^4
Span, outer rooms:	20 ft
Maximum Shear Force (DL only):	4000 lb
Maximum Shear Stress (DL only):	0.91 ksi
Maximum DL Moment:	20 k-ft
Allowable Live Load:	74.4 psf
Live Load deflection:	0.38 in (L / 630)
Span, Interior rooms:	15 ft
Maximum DL Moment:	11.2 k-ft
Allowable Live Load:	184 psf
Box Girders:	
Area:	18.37 in^2
Moment of Inertia (I):	559 in^4
Shear stress (DL):	0.91 ksi
Allowable Live Load:	114 psf
Columns:	
Applied Load:	22.3 kip
Compressive stress:	1.1 ksi
Allowable stress:	80.0 ksi

The load factors correspond to a ϕ factor of 0.68 for a DL/LL ration of 0.4 using the normal 1.2 DL factor and 1.6 LL factor. In addition, the 35 ksi yield stress assumed for the previous analysis is less than the 38 ksi average yield stress obtained by test.

bottom flange of the floor joist. Undoubtably, the centering was not supported by staging, thus before the mortar set, the floor beams were subjected to the dead-load of the brickwork. Whether or not staging was used, it is prudent to assume that the dead load of the brickwork is carried entirely by the floor joist. Thus, the preliminary analysis serves to establish stress levels in the beams before the infill, flooring, or any live load is applied. The possible structural contribution of the brick vault is restricted to the weight of the light infill leveling course and the wooden floor, and of course, the applied live load.

Having studied the architect Robert Mills earlier structure in Charleston, South Carolina, it appeared that a reconsideration of the function of the joist-arch system under live load was in order. If one considers the longitudinal structure as a curved surface with the iron beams acting in tension as edge beams, and the jack-arches supplying the necessary compressive forces would such an analysis reveal a safe live load capacity of more than 100 psf?

All earlier examinations of the Custom House interior skeletal frame focused upon the cast and wrought-iron components assuming the massive exterior load-bearing stonework was more than adequate. In like manner, the jack-arch floors were assumed to carry their load transversely to the iron floor beams and not be heavily stressed. If, however, the brickwork supplied the compressive resistance to floor loads in the longitudinal direction, the compressive strength of the brick was needed to confirm the analysis. Test revealed a compression strength of 6,050 psi and with an assumed deviation of 1,500 psi, the brickwork appeared to be more than adequate (Tice 1995, 44–45). The jack-arches were laid up with natural cement-sand mortar as required in the original specifications.

If the brick vault spanning longitudinally with the iron joist providing the necessary tensile strength, one must assume that the bond between the mortar at the base of the arch and the web of the 9-inch beam is

adequate. According to early concrete specifications, a value of 240 pounds psi is an appropriate working stress. The light fill was assumed at 50 pounds per cubic foot (pcf), and the southern pine floors at 50 pcf, including sleepers used to attach the floors to the fill (Hool et al. 1918, 265–68).

With the material properties of the structural components in hand, an analysis using Algon's 20 node solid system, as depicted in the illustration, served as the basis for the analysis. With a live load of 100 psf, the results revealed a deflection of 0.56 inches and stresses in both the longitudinal and radial directions, which were quite acceptable and well below working stress levels. The sheer stress at the interface of the iron web and the mortar was found to be 142 psi, well below the 240 psi thought to be a safe value. At a value of 124 psf live load, the analysis reveals that the structure can sustain the desired 100 psf throughout the building. Such a result will allow increased flexibility in utilizing the public space within the Custom House, Table 3.

Table 3 Summary of Finite Element Analysis

Material properties for the brick will be assumed as:	
f'm 1800 psi	
v=0.11	
Modulus of Elasticity	1800000 psi
Modulus of Rigidity	720000psi
f't	320 psi
Material properties for the iron will be:	
Young's Modulus	24000 ksi
Yield Stress	38000 psi
Ultimate Stress	50000 psi
Design Shear Strength $(v_n)^{10}$ full x-section	90000 lbs
Design Shear Strength (v_n) cut section	34500 lbs
Model:	
644 nodes	
648 elements can divided into shell elements and beam elements	
Arch span 5 ft = 60 inches	
Thickness of arch 4 inches	
Beam elements use iron properties	
Length of beam 10 ft = 240 inches	
I Beam section:	
Height of Iron Beam	9.0625 inches
Width of top I beam	4 inches
Width of bottom I beam	4 inches
Thickness of flange	0.5 inches
Thickness of I beam	0.432 inches
Load:	
Z axis: Load / area 100 pounds per ft^2 = 0.694 lbs / in^2	
Constraint:	
Pin support in X axis and Z axis at 4 corners	

Note: Model by Femap700 Out put by CSA/Nastran Unit: force (lb) : length (inch)

The results also indicated that the jack-arch floor system supported with iron edge beams can sustain loads by composite action providing there is sufficient bond strength between the iron joists and the brick arches, Figure 13.

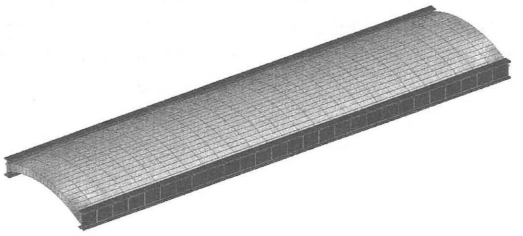


Figure 13
(2002) Three dimensional mathematical model of one bay of the floor system used by the author (Institute for the History of Technology and Industrial Archaeology Archives, Morgantown, WV, USA)

A more sophisticated analysis considering cracking of the brickwork in tension may reveal new insights into the behavior of the arch floor system whether it be constructed in brick or concrete. With the present analysis, however, a load test on the Custom House floor would be the most important means of confirming the structural analysis, and provide insights into other buildings using this system.

Together with other mid-century skeletal framed iron structures, the Wheeling Custom House stands as an important landmark in the history of 19th century building. By the end of the century, the skeletal framed high-rise building became the hallmark of American engineers and architects, and transformed the appearance of American cities.

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The old power plant at Silahtarağa in Istanbul

Binnur Kıraç
Mevlüde Kaptı
Sadettin Ökten

Industrial buildings are largely designed considering their machine equipment and production process. Therefore, their architectural development are slightly investigated by architectural historians in contrast to other structures. These engineering buildings have been recognised and gained importance by help of the industrial heritage concept. And they are analysed and evaluated in the context of this concept.

In these buildings developments in technology have deeply influenced architectural design and form. The analysis of these structures gives us important information about technological and consequently structural development process.

Ottoman empire had attempted to join the industrial revolution developed in Europe by westernisation movement generated especially in mid 19th century. In this extend some factories have been founded in the country in order to realize the western lifestyle. These buildings have been constructed by following western style and technology and by the time due to changes in production ways have lost their functions and have been abandoned. In Turkey around 90's they have been considered in the content of industrial heritage and gained importance.

At the beginning of 20th century the illumination of Ottoman capitol Istanbul by electricity had become a current issue as an extension of westernisation. As a result it had been decided to build a power plant in the city.

In this paper Silahtarağa power plant which is the first electricity producing plant in Turkey has been studied as an important edifice of industrial heritage.

Brief Historical Background

The first proposal for electrification of Istanbul had been made in 1878 by a French firm but given no result. In 1908 the Ministry of Public Works prepared a regulation about the issue since electrification of the city would be a model for other cities of the empire. Under the rules of this regulation an invitation has been made for construction bids. Among eight firms submitting bids the Hungarian firm Gans has been awarded for the venture. (Ergin 1995, 5: 3692)

In 1910 the firm has taken privileges of construction and operation of the establishment for fifty years and founded a domestic firm Ottoman Electrical Company. Later the firm Gans made an agreement with other two companies and capacity of the plant has been increased from 3000 KW to 14400 KW. (Önay 1972, 31)

Because there is no powerful stream enough to operate a hydraulic plant in the vicinity of Istanbul a steam plant has been the solution. The best place for the plant has been determined on the deep inlet Haliç at the junction of two streams (Aytar 1957a, 5). Due to the easy transportation of coal through the natural harbour Haliç and sufficient supply of fresh water from streams and effective distribution of power to whole city this place has clear advantages (Figure 1).

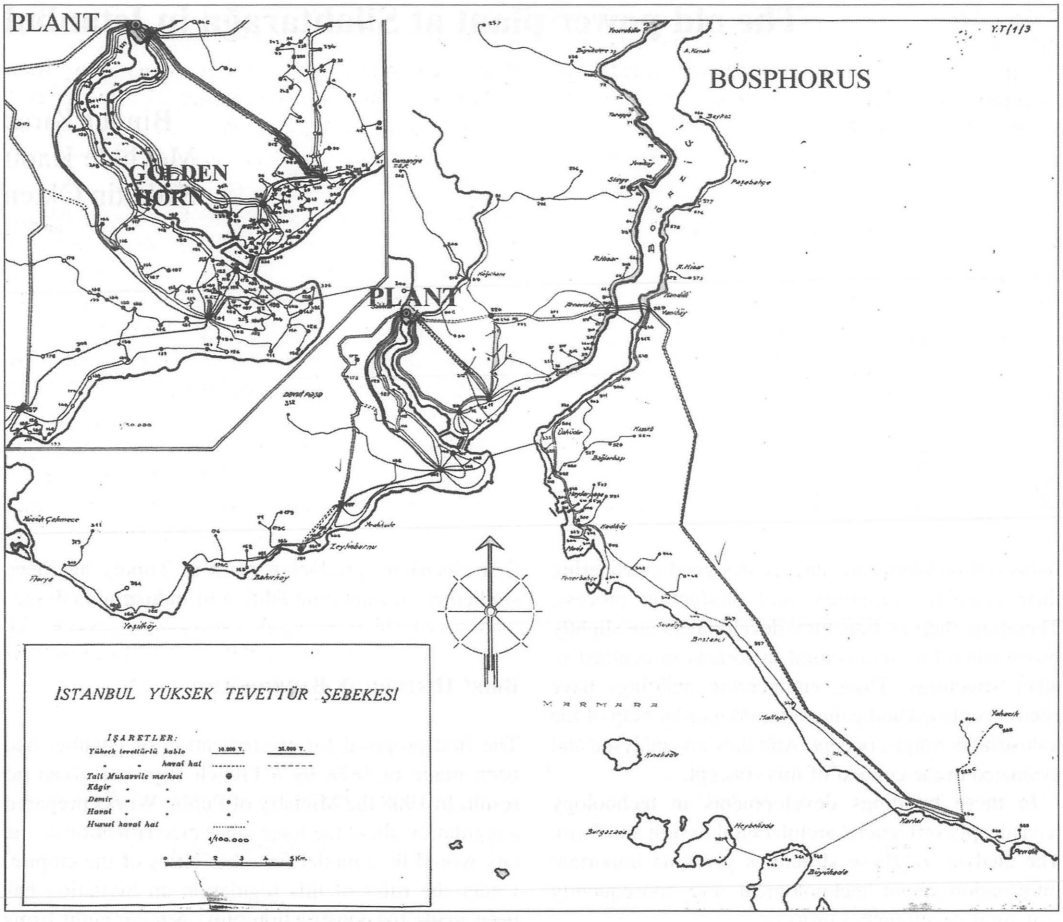


Figure 1
Power distribution network of the Plant

In electrification of Istanbul the city has been divided into two parts as European and Asian sides and a transmission cable would cross the Bosphorus under the sea (Erengil 1957, 3). The plant and power distribution network have been planned to finish in 1913 but because of war and flood they have been completed in 1914 (Önay 1972, 33).

General Information

The power plant has been founded on the area of 120 000 m^2 (Acar 1976, 323). From the first general plan of plant dated 1911 its understood that the plant has been designed for four expansion stages.[1] It has been thought that four boiling rooms would be placed in south-north direction in front of the engine room. General rule of planning of the plant was to allow any capacity increase in future. The longitudinal axes of boiling and engine rooms have been placed in such a way that new expansions could be realised easily. This planning furthermore has facilitated passing of steam pipes and entering to buildings.[2]

The plant completed in 1914 has composed of the following buildings: the main production unit with T shaped plan containing one engine and one boiling

rooms, pier and quay, storage and transportation system for coal supply, channels for fresh and waste water, repair and maintenance workshops, administration office and residential buildings for personnel[2, 3] (Figure 2).

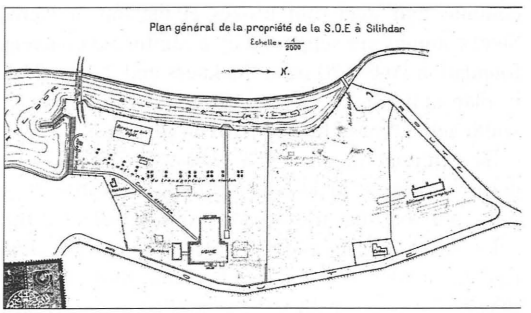


Figure 2

The main production unit has been placed near the city road. The pier on the shore has been connected to the plant by a monorail system of 225 m in length transporting coal from boats to storage area and from there to boiling room. (Cengizkan 2001, 5)

The capacity of storage area was around 40 000 tons of coal. Cinder coming from furnaces in boiling room has been used in producing briquette by mixing it with cement. This product was for sale in market and a protection material for underground power distribution system.

Cooling water taken from stream after filtered and set-aside has been passed through condensers and delivered to Haliç being slightly warmer by the outlet channel (Acar 1976, 325).

The plant has continued to produce electricity in its original capacity until 1920. In 1921 two new boilers have been added to the existing boiling room and a new engine room (engine room 2) has been constructed containing a turbine and a generator. The extra power produced by new equipment was expected as around 12 000 KW but the turbine could not be operated in desired productivity. Because of partly for this reason and partly increased necessity for electricity the turbine portion of the plant has been expended in the years 1923, 24,29. The existing boiling equipment has provided the continuously increasing need for electricity with great difficultly until 1928. In 1929 a new boiling room (boiling room 2) has been constructed containing for new boilers. It is seen in general plan dated 1931[4] that the all expansion works have been realised following the ways proposed in the original plan dated 1911. In 1939 due to the increasing need of electricity another boiling room (boiling room 3) has been constructed with two boilers. And total capacity of the plant has arrived to 70 000 KW (IE.T.T. 1940, 71). In 1944 a new engine room (engine room 3) and 1956 a new boiling room (boiling room 4) have been added to the plant and then the total producing capacity has arrived to 100 000 KW in 70's.[5] The general plan referred to 70's shows the last configuration of the plant just before closing (Acar 1976, 330) (Figure 3). There were existed four engine rooms and four boiling rooms in 1983 the year plant was closed. But the first engine and boiling rooms (rooms 1) and first added engine room (engine room 2) have survived until present day in their original conditions. Besides the engine room dated 40's, and boiling room dated more recent years has also survived until now.

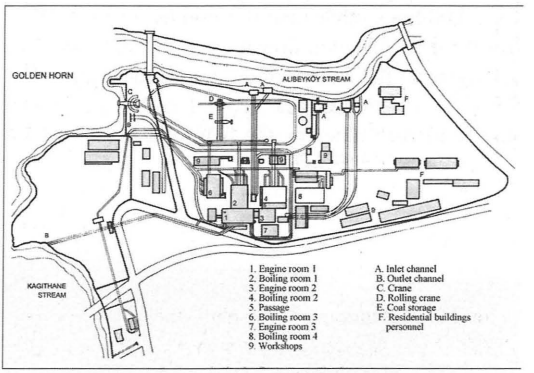


Figure 3

The plans dated years between 1912 and 1970 show that the plant with its original buildings and expansions has become a large complex. Plant and working units were located at south on Haliç shore and residential units moved to north. At the south there were plant and office buildings, workshops, coal storage and lodgings for director and guards. At

the north far from pollution of the plant there were housing facilities for workers and restaurant.

Constructional Analysis of First Buildings (Buildings 1)

The report dated 1912 has documented the first decisions about construction in the founding stage of the plant and specifications of spaces and equipments. It also defines the operation scheme of the plant. In this report the dimension of buildings have been given as following values: for boiling room length 37.40 m, span 24.80 m, height from ground 3.60 m, height for space 11.40 m and for engine room the corresponding values are 50 m, 22.30 m, 6 m and 14 m respectively. Besides. it is declared in this report that the buildings have been constructed little longer than project values to allow expansion. From this report it is understood that the engine and boiling rooms 1 have been constructed on reinforced concrete platforms as metal skeleton filled with brick (Figure 4). And these buildings have been equipped with cathedral type windows for daylight and fresh air.[2]

It could not be arrived to any information about these buildings other than those given in this report. But there are detailed drawings in the state archives belonging to the engine room 2 constructed in 1921. Since the existing engine room 1 and 2 are greatly similar to each other by the help of the projects for engine room 2 and field observations the construction of first building has been tried to analyse.

The Project Data for Engine Room 2

The structural system is consisted of latticed steel columns and steel roof trusses at the top of them. Steel columns are supported by a reinforced concrete foundation slob 0.70 m in thickness and 27.4 × 23.4 in plan dimensions. There is a brick wall 0.52 m in width and 3.0 m in height between columns.

The report dated 1918[6] about drilling work performed in the field declares the soil profile, it is quite possible that this information has affected the selection of foundation system (Figure 5). The foundation slab is supported by reinforced concrete piles 7.3 m in length 25/25 cm in cross section.[7] Reinforcement is made of 4• 20 longitudinal bars and •6/30 stirrups. The piles have been inserted 0.45 cm into the slab. The slab has also been reinforced at both surfaces, upper and lower, in two directions by •20/25 bars as a grid and •8/50 vertical stirrups. The pile groups have been located just under the heavy machines. The slab and piles were assumed to share the total weight of the upper structure; this can be understood from the technical report prepeared for the foundation system.[7] There is also an intermediate story at level 7.4 m made of steel and supporting the generators. The condensers have been placed on the main floor.

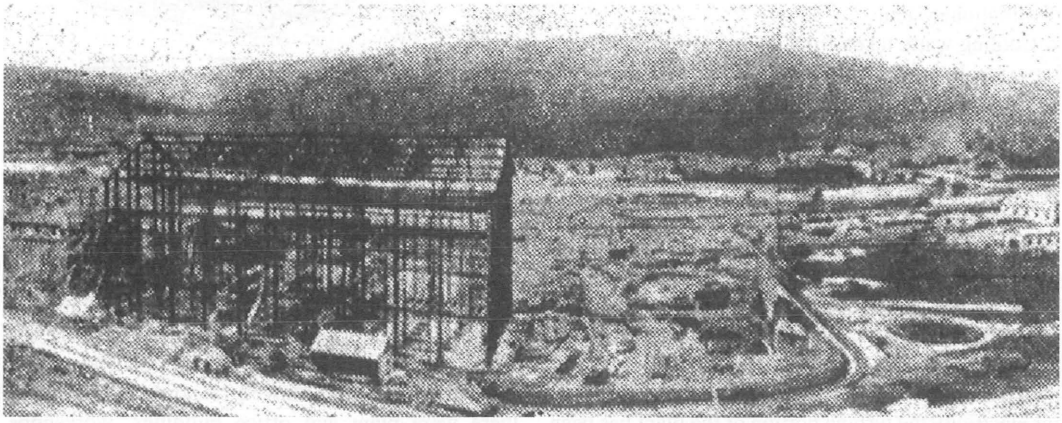


Figure 4

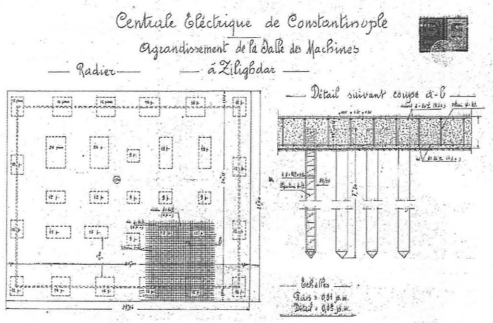


Figure 5

The inner and outer dimensions of the building are respectively 20 × 25 m and 20.24 × 25.32 m. Inner eave and ridge heights are 19.9 m and 24.5 m. Steel trusses spaced 5 m in bay width have covered the span of 20 m. These are supported by riveted lattice type of steel columns supporting a heavy crane at level 147m and having tiny sections upwards of this level[8, 9, 10] (Figure 6, 7, 8).

There are three rows of windows on the façade of the building. The window system has been applied as a metal construction in harmony with whole building.

The outer walls of the building have been formed by a thin brick filling placed between light I-beams supported on the outer surface of columns. Inner and outer surfaces of walls have been plastered. To keep the filling in its place and to provide stability for the system in the direction perpendicular plane of trusses a horizontal bracing system rigidly connected to the columns has been arranged. The total metal construction has been exhibited on façades. Between engine rooms 1 and 2 there are the office room for chief of the plant 5 × 6.7 m in plan dimensions and a passage 2.5 m in width.

Field Observations for Engine Room 2

The inner dimensions of the building have been measured as 20 × 25 m just as the same value given in the project. In the west, façade lines of two engine rooms (1 and 2) are same but engine room 2 has been constructed narrower than engine room 1. Eave height is measured as 19.7 m but it is 19.90 m in the project. In general, the building has been constructed obeying the project values with one exception observed in column details. Construction detail is shown in figure 9.

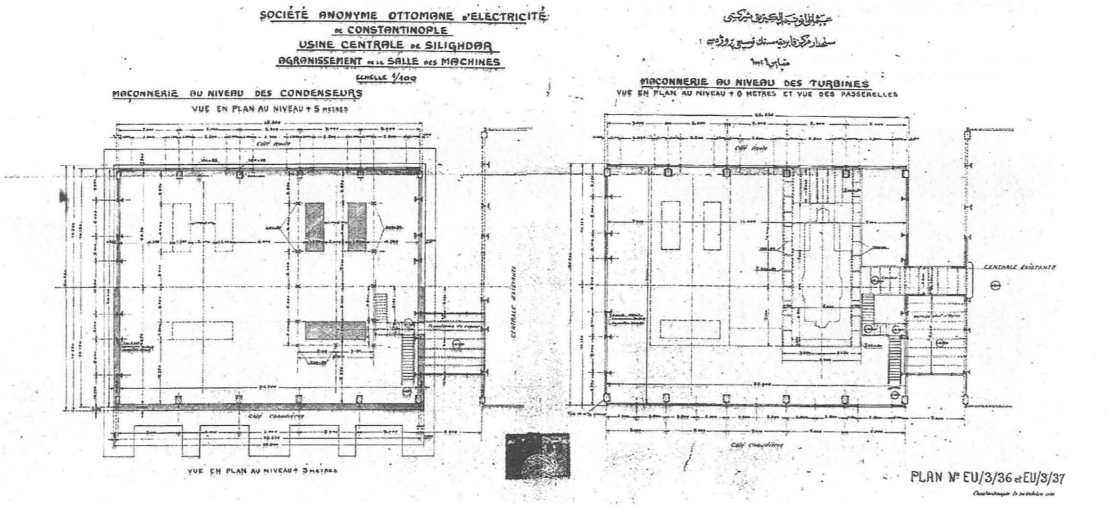


Figure 6

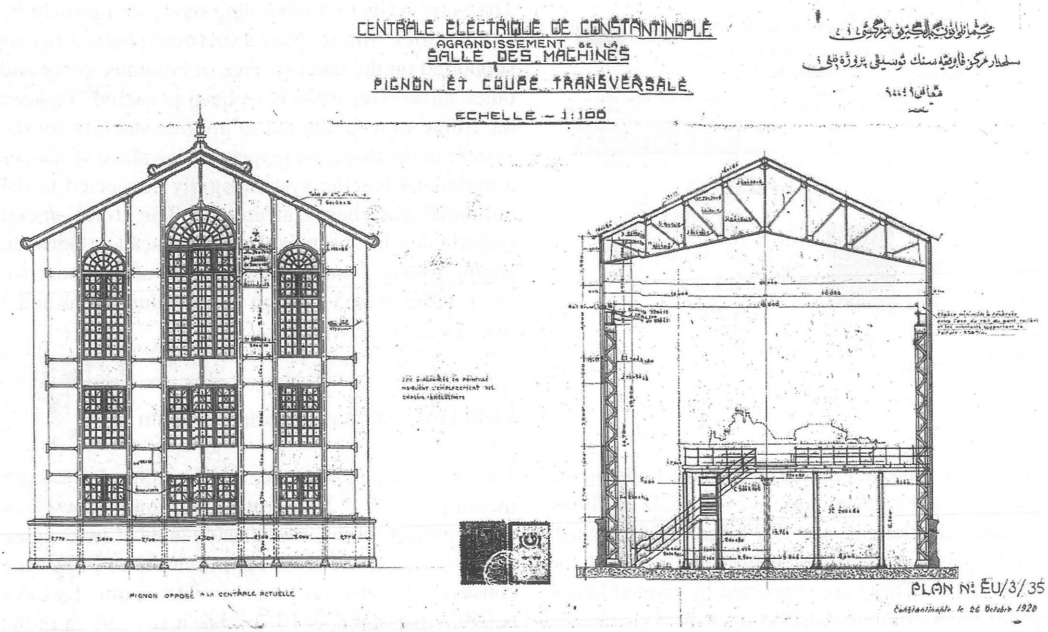


Figure 7

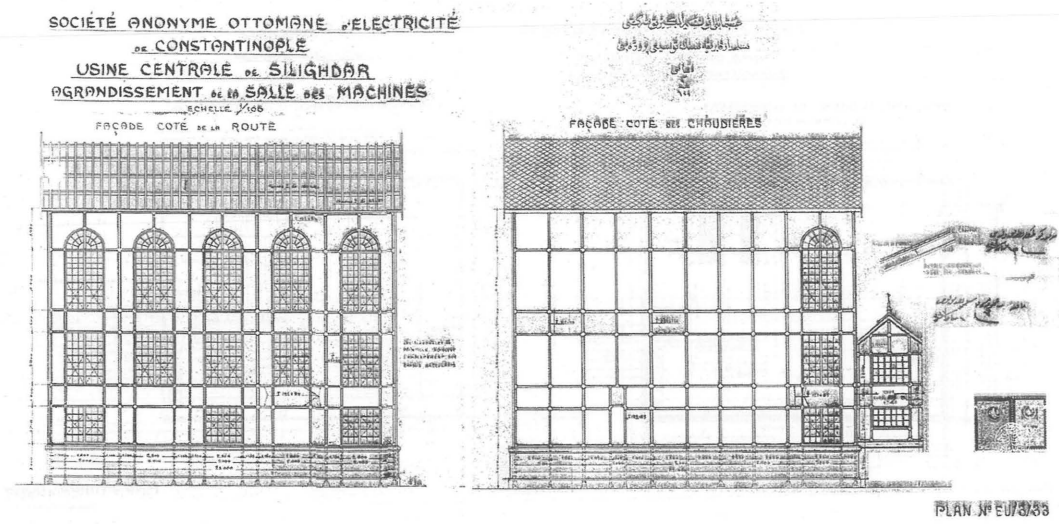
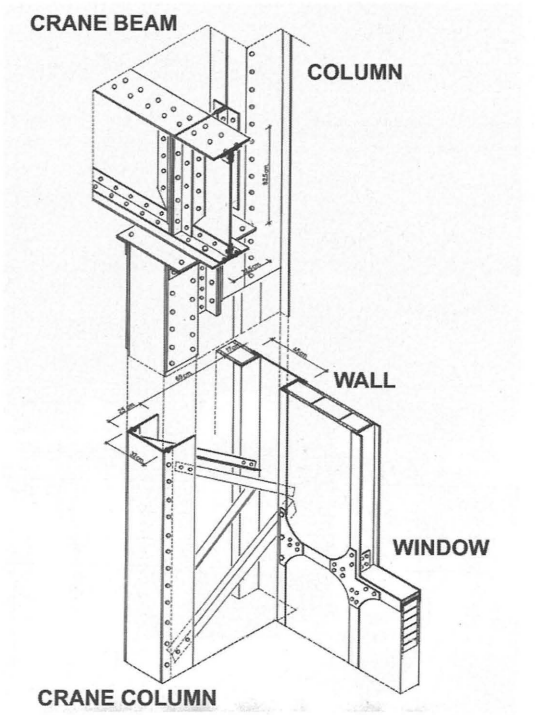


Figure 8





Figures 9a and 9b

Field Observations for Engine Room 1

The inner dimensions of the building have been measured as 23.36 × 50 m namely the width is larger than the value given in the report dated 1912 but the length is unchanged.

There is a great similarity between engine rooms 1 and 2. The only difference is observed on the details of steel columns. In the drawings for engine room 2 column details are same as the column construction in engine room 1. It shows that the engine room 2 has been designed similar to engine room 1 but in application different column details have been used (Figure 10).

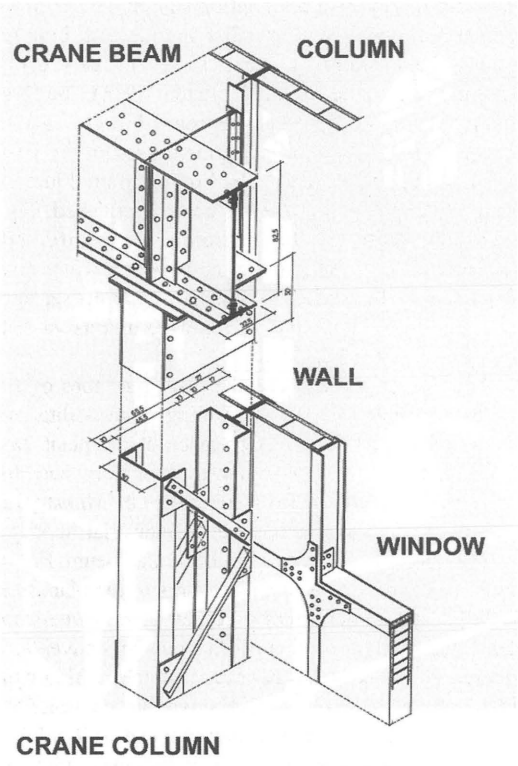
The intermediate stories supporting generators have been observed as made of reinforced concrete in both engine rooms. It is thought that this change (from steel to reinforced concrete) has occurred by the renewal of tribunes with time.

It is not possible to enter the boiling room 1 and make its measurements because of the negative conditions of the building. But from outer observation it is said that this building has great similarity to engine room 1.

Monorail Construction

Coal for furnaces transported by boats has been transmitted to the coal storage by help of the crane on the pier and the monorail conveyor (Aytar 1957, 5). From here to furnaces a similar system has been used for coal transportation. After burning cinder has been carried to the briquette workshop (Cengizkan 2001, 7) (Figure 11, 13).

This equipment has worked until 1940 without any problem. In the following years due to the weak soil conditions foundation settlements on columns have been observed on monorail system causing heavy damage. There was a serious necessity for repairing (IETT 1940). In 1955 during the modernizing activities of the plant in general the monorail system



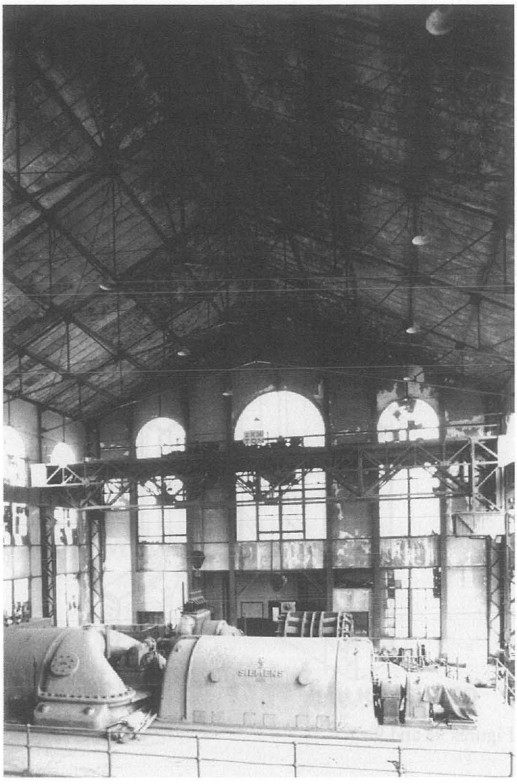


Figure 10a and 10b

has also been renewed. There is no evidence from this equipment to our present day. It is predicted that the whole equipment has been removed together with boiling room 4 in 1985–86. Today the pier has been closed by a concrete wall and abandoned. The following definition of monorail system depends on the exiting documents. From the drawing dated 1928 it is observed that there were a pier toward Haliç in dimensions of 5 × 30 m and a quay of 70 m on the shore with a crane at its mid point.[11] The construction system is composed of two rows of piles with 5 m apart from each other and vertical retaining walls between them. The space between these walls has been filled with soil. The material used in piles and walls has been predicted as timber depending on drawings (Figure 12).

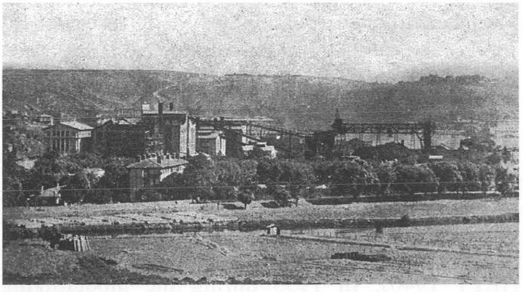


Figure 11

The rotating crane on the quay has also been supported by piles.[2] This crane could cover the circular area 8 m in diameter and fill up a bucket at the level of 19 m and the bucket has transmitted the coal to the monorail system at the level of 16 m (Cengizkan 2001, 8).

The plan dated 1923 shows that the coal storage

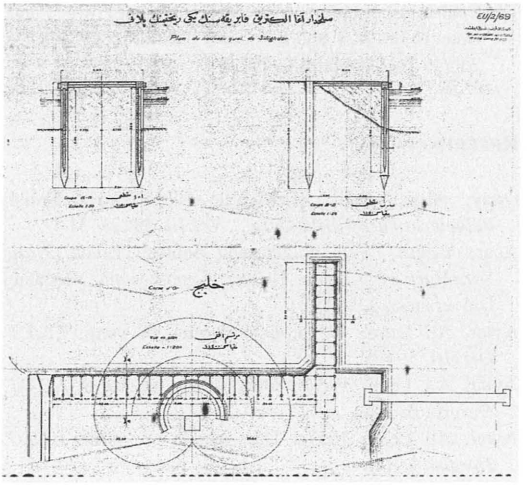


Figure 12

was located between the plant and the stream and equipped with a rolling crane system reaching the whole area of 50 × 124 m in dimensions[12] (Figure 13).

Present Situation of The Plant

The plant has been nationalized in 1937. It has been directed by the Municipality of Istanbul until 1970. At this year Turkish Electricity Association took over the establishment. Production of electricity has finished in 1983 because of lack of the cooling water in the stream. From this year up to now plant has been working for a power distribution station. In our days the existing buildings are first engine and boiling rooms (both number 1, dated 1914) in fairly good conditions, engine room 2 (dated 1921), boiling room 3 (dated 1939) and engine room 3 (dated 1944). In these buildings whole equipment used in the past for production are existed. But boiling room 2 just in front of the engine room 2 has been demolished. The surviving parts of this building are reinforced concrete platform supporting the upper structure and few details. The boiling room 4 starting to the service in 1956 has been completely removed and its vacant lot is used as a storage area.

After loosing its function the plant also goes on to exhibit its identity (Figure 14). During the rehabilitation works of the district the importance of the plant has been recognized and a serious attemp has been made to preserve it. The plant has been registered by Ministry of Culture in 1990 as a monument of industrial heritage and intended to refunction as Industrial Museum. From this year to now the restoration works of the plant has been put on the agenda. But besides some ownership problems there are other difficultics in convention process of this large and important complex. Although all negative conditions it would be suitable to refunction the plant specially as energy museum and so it will be preserved and reused in future in harmony with its original function.

Notes

1. Exploration map for the plant, which will be constructed in Silahtarağa. Date 11.05.1911and number 34E/750, (number Republic of Turkey Prime Ministry,

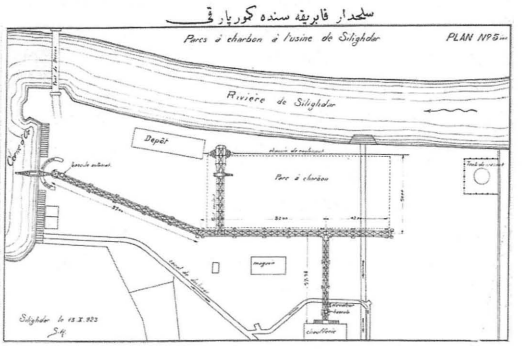


Figure 13



Figure 14

General Directorate of State Archives-RTPMGDSA 230/48.73.2).

2. «Memoire descriptif et justificatif des dispositions dans l'Usine»; Date 09.09.1912 and number 34E/734, (RTPMGDSA 230/48.73.4).
3. The plans of magazine, workshops and other buildings. Date 19.07.1921 and number 34E/774, (RTPMGDSA 230/48.74.14), plan U 160.
4. General plan of Silahdârağa Power Plant. Date 05.06.1933 and number 34E/820, (RTPMGDSA 230/49.78.7).
5. Report from Turkish Electricity Association Archives.
6. Drilling works on the field to observe soil conditions in the area of Silahtarağa Power Plant. Date 01.03.1919 and number 34E/768, (RTPMGDSA 230/48.74.7)
7. The plans of changing to be made in Silahtarağa Power Plant. Date 31.01.1921 and number 37E/771, (RTPMGDSA 230/48.74.11).
8. The plans of changing to be made in Silahtarağa Power Plant. Date 31.01.1921 and number 37E/771, (RTPMGDSA 230/48.74.11), plan EU/3/36, EU/3/37.
9. The plans of changing to be made in Silahtarağa Power Plant. Date 31.01.1921 and number 37E/771, (RTPMGDSA 230/48.74.11), plan EU/3/35.
10. The plans of changing to be made in Silahtarağa Power Plant. Date 31.01.1921 and number 37E/771, (RTPMGDSA 230/48.74.11), plan EU/3/34, EU/3/38.
11. Pier and quay plans for Silahtarağa Power Plant. Date 20.05.1928 and number 34E/809, (RTPMGDSA 230/49.77.7), plan EU/2/69.
12. Coal transportation system in Silahtarağa Power Plant. Date 19.08.1924 and number 37E/800, (RTPMGDSA 230/49.76.13), plan EU/4/120.

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Measure and map: Alphand's contours of construction at the Parc des Buttes Chaumont, Paris 1867

Ann Komara

The urban renewal projects undertaken in Paris by Napoléon III during the Second Empire (1852–1870/71) exemplify French industrial and technological expertise as applied to the realm of landscape design. The Parc des Buttes Chaumont, christened April 1, 1867, can be singled out for examination as it demonstrates a sophisticated marriage of art and industry as well as highlights the technical skills and sophisticated expertise of the cadre of engineers and designers working under Haussmann, the Prefect of the Seine. Jean-Charles Adolphe Alphand's (1817–1891) transformation of a notorious quarry site into a celebrated park physically demonstrates the results generated from a precise topographic survey that reconciled and used horizontal and vertical measure as codified on a sophisticated contour map depicting the landform. The noted scholar of cartography, J. B. Harley stated that it is « . . . a major error to conflate the history of maps with the history of measurement (Harley 107).» I suggest, in contrast, that the very convergence of measure and map is the construct underpinning the production of the Parc des Buttes Chaumont. The contour map and topographic rendering of the park site that Alphand published in *Les Promenades de Paris* (1867–73) are specific ideological tools for comprehending not only a unique spatial condition but also for envisioning the city as a technical marvel.

To understand how this condition was achieved this paper examines the relationship between the physical surveying of the site and the resulting cartographic representations of the park landscape. A history of surveying in France is lengthy and not the point of this paper, having been well covered by Buisseret (1992) and Konvitz (1987) among others. Nonetheless, a brief summary of this history helps to contextualize the work of the Second Empire and establishing the design, construction and reception of the Parc des Buttes Chaumont as a model of technical achievements.

History of French land measures and surveys

The history of land measure and surveying is linked to the scientific revolution and national exigencies. The knowledge was directly applied to government and military efforts and to urban and landscape design. The French government subsidized efforts undertaken at the Académie des Sciences; during « . . . the seventeenth and eighteenth centuries, France became the leader in topographic mapping, developing methods which became standard and later were widely adopted elsewhere (Thrower 73).» French engineers and military surveyors trained in the centralized école system. The curriculum and philosophy at the École Royale des Ponts et Chaussées in Paris, from which Haussmann drew many engineers and designers, strongly linked technical applications and design theory. This is demonstrated by a map drawn by a civil engineering

student as part of a final examination sometime in the late eighteenth century. It depicts an imaginary territory which Konvitz (1987 Plate 7) suggests is an illustration of the teachings of Abbé Marc-Antoine Laugier regarding the essential similarity between urban planning and landscape design. Alphand trained at the École from 1838 to 1843, and this philosophical link is implicit in Alphand's work at the park. Furthermore, he would have been well aware of innovations and applied practices in land measure and surveying. To most clearly demonstrate the relevance of this in Alphand's work, it is helpful distinguish the lineage of horizontal, triangulated measure and vertical, elevation measure.

Horizontal surveys

By the early nineteenth century, triangulation surveying had become standard in the production of data for horizontal distance and boundary measures. The diagram after Frisius (1553) demonstrates the principal of the triangulation method, in which, « . . . once the length of the base line is established, surveyors can measure angles from either end by sighting on some distant object. A triangle results, and geometry solves the lengths of the unknown sides. Then, from these sides, more triangles can be laid out and measured (Bricker 38)». Tools such as Ramsden's great theodolites of the late eighteenth-century refined the accuracy for sighting distances and measuring the degree of the angle, and material standards for chains and rods with low coefficients of expansion assured exacting distance measures for the calculations.

France instituted the earliest national survey mapping. Jean Picard (1620–82) fixed relative horizontal positions astronomically and laid down a chain of triangles based on the Paris meridian, as shown in the Académie Royale's map of 1670. The survey baseline established at the Observatoire that is a datum for survey work supported by the Cassini family, including the «Carte de France» of the 1680s. Jacques Cassini de Thury (1714–84) and his son, César François verified Picard's meridian and documented their work in their 1740 publication, La Meridienne de Paris. Their work established the accurate extension of triangulation as the standard upon which French surveys proceeded, as shown in the detail of the 1744 map by Giovanni Maraldi and Jacques Cassini and the *Carte de Cassini* published between 1756 and 1793). (Konvitz 6–10) Through these pioneering efforts, France was the first country to be mapped on the general principles of modern survey wherein the survey proceeded «from the whole to the part . . . [by establishing] a rigid geometrical framework of triangles before filling in topographic detail by local observations of angles and distances (Singer Vol. IV, 605).»

Edme Verniquet employed triangulation to produce an important cadastral survey map of Paris based on the meridian of the Observatoire.[1] Surveyed in quadrants, the 1791 «Plan de Guillot», included trigonometric tabulations and tables of distances. It highlighted street patterns, especially those superimposed on the old perimeter walls, major monuments and some residential data. Additionally, it provided some topographic clues; of particular note are the graphic indications of quarrying operations at the buttes of Montmartre, Belleville and Chaumont.

Verniquet's extensive work served as the foundation for much of the design work in nineteenth- century Paris, including Haussmann's. As Konvitz aptly writes, «Often engineers and architects viewed cities as they did rural landscapes, as areas to be reshaped into a new, more productive pattern of territorial organization. Maps based on thorough surveys were used to record and coordinate all public works projects and to calculate the value of property that might be expropriated (Konvitz 110).» Evidence for this practice is an 1811 plan proposing the Canal St. Martin shown drafted over Verniquet's survey. Built between 1821 and 1825, it is clear that the canal was not discreetly set into the existing urban fabric, but rather, designed as « . . . an agent of change whose presence would create opportunities for commerce and industry along its banks (Konvitz 111).»

Vertical or elevation surveys and the depiction of topography

Parallel developments were occurring for the depiction of topography. A topographic map «presents the horizontal and vertical positions of the features [as] distinguished from a planimetric map by the addition of relief in measurable form (Thompson 254).» Drawn contours, also known as isohypses, were well established in France by the early nineteenth-century,

their origins and applications as coastline and hydrographic descriptors for channel depths having been understood by the eighteenth-century. Early debates concerning their application to landform lead Marcellin Du Carla, a Languedocian geographer, to published *Expression des nouvellements, ou Méthodes nouvelle pour marquer rigoreusement sur les cartes terrestres et marines les hauteurs et les configuration des terreins* (1782). In what is today considered the «the first fully developed exposition of contour lines», Du Carla wrote,

> man cannot see the world as it is by looking at it; reality emerges as a synthesis of information on paper . . . With contour lines on a map . . . it becomes possible to visualize what can and cannot be seen from any one point. Contour lines are a language and from them a three-dimensional image of space can be constructed in the mind (Konvitz, 77–78).

Employing contour lines to convey the shape of a landform gained currency through Pierre-Simon Girard. His contour map of Paris (1812) recorded all data directly on Verniquet's «massive geoditic survey of Paris . . . All measurements of the same value, corresponding to an identical elevation [above a datum] along the east-west and north-south dividing lines were connected by line, as much as possible at one-meter intervals . . . Another map was also engraved using hatch lines to express elevation instead of contour lines (Konvitz, 100).»

The use of hachures or hatch-lines to represent topography evolved into specific techniques to describe the angle and direction of slopes and landforms. In one traditional method,

lines are drawn down the slope in the direction of the steepest gradient; conventionally, they are drawn closer together where the slope is steeper. Another method employs the same number of lines per inch, but each one is proportionally thicker . . . where the thickness of the individual hachure is determined according to the angle of the slope. Another adaptation is where the hachuring is assumed to be obliquely lighted, usually from the north-west, but this is only effective in regions of strong relief, with sharply defined ridges, as in Switzerland, where the method was developed on the Dufour map (Monkhouse and Wilkinson, 96–97).

Developments in hachure representations led to proscriptive techniques such as the hachure meter shown in Enthoffer's *Manual of Topography* (1869–70). While the hachure method such as that shown in Dufour's Swiss *Atlas* of 1833–63 is an invaluable aid to visualizing topographic relief on a maps, its chief disadvantage was the lack of absolute information or physical accuracy without inserting numerous spot elevations. Girard's strategy of using both techniques conveyed both quantitative and descriptive information about the site and the design proposal and was typical for that period. Alphand emulated this practice for the maps of the Parc des Buttes Chaumont.

Survey work during the Second Empire

The practices of topographic surveying as a means towards envisioning the city underpin Haussmann's building program and provide a direct link to Alphand's work. Their attempts to refashion an entire city «posed technical problems for which there were no ready solutions —no accurate [detailed topographic] map of Paris existed in 1850 and one had to be made, starting with the triangulation of the whole city (Pinckney 5).» Haussmann's plans could not have been carried forward without accurate surveys; in 1853 he organized a *Service du Plan de Paris* under supervision of the Chief Surveyor, Deschamps. (Pinckney 56)

Debates at the time regarding the best method for rendering the exact disposition of three-dimensional landform as opposed to simply producing a horizontal plan generally favored the methods adopted by Deschamps. Building on Girard's contour map and Verniquet's survey, Deschamps' corps of surveyors carried out an exacting survey. The basic technique of topographical land surveys were well established: « . . . into an accurate framework of triangulation the topographical detail was inserted by plane-table, detail traverse, or chain-survey methods . . . (Singer Vol. IV, 441).» To accomplish this, towers were set up around the city and vertical and horizontal data were derived from theodolite measurements with the data based on leveling, triangulation and trigonometric calculation for all areas. This well-known effort received attention in newspaper editorials and provided fodder for numerous political cartoons, such as those by the cartoonist Cham (the pseudonym of Amédée de Noé).

What emerged «from this work was a large master plan of Paris, a copy on a scale of 1 to 5000 that Haussmann kept mounted in his own office, and many working copies on smaller scales (Pinckney 56).» Haussmann's survey team simultaneously prepared detailed cadastral plans and contour relief maps of the city at matched metric scales based on mutual datums of the Paris meridian and mean sea level. The concurrence between maps reflects decisions about standardization of scale and contour intervals dating from 1791 when

> the Paris *Académie des Sciences* . . . defined the meter as 1/10.000.000 of a quadrant of the terrestrial meridian. This led to the concept of 'natural scale' in cartography whereby one unit of length on the map is represented by a given number of like units on the earth. This so-called representative fraction (R. F.) was first used in France in 1806 (Thrower 81).

The systematic survey of the Buttes Chaumont site provided the level of knowledge and detail Alphand required as a predicate for his design and construction of the park. Like Girard earlier in the century, Alphand presents the Parc des Buttes Chaumont in two maps registered at the same scale; a contour map and a rendered site plan. Consideration must now turn to this pair of plans to examine their relevance, to discuss how Alphand used the information in them, and what they signify.

Alphand's maps of the Parc des Buttes Chaumont

The maps were published in *Les Promenades de Paris*, Alphand's two-volume catalogue raisonné of works accomplished during Haussmann's administration. Throughout *Les Promenades*, Alphand celebrated design solutions arrived at through engineering and design invention. He detailed the innovations employed to install and maintain the works and tabulated, enumerated, and catalogued his civic improvements. For Alphand, studying the terrain was a very interesting and delicate operation that was fundamental to all else in the design process.[2] (Alphand 1984, L) His projects commenced with shaping the terrain, then adding the planting and finally scripting the circulation routes. It is no surprise that his work at the Buttes Chaumont commenced with a critical step: the determination of the physical landform by way of careful mapping and geological studies.

Relevance

The contour map reconciled horizontal and vertical measure and tied the project into the overall topographic information of the city. The technical mastery evidenced in the execution and codification of the survey information is daunting. Even using sophisticated survey equipment, conducting a survey on the sixty-two acre (25 hectare) site would have been extremely difficult. The site, an old quarry and former dump, presented some inherent difficulties that included a highly irregular landform of steep quarried cliffs, declivities and cess-pools filled with offal and refuse. A careful examination of the *Plan des courbes de niveau* (contour plan) aides in understanding Alphand's engineering feat. The plan, at a scale of 0m00–05 over 1m00 uses a 1-meter vertical contour increment. Black lines indicate existing or original site contours and red [darker gray] lines indicate «l'état actuel», or the «as-built» conditions of Alphand's designed park. In the enlarged detail the overlaying of these two sets of contours demonstrates the variation between the conditions. In the quarry, the lowest elevation is at 46 m, with 52 m the most consistent depth of the mine. The highest points shown are at 97–99 m. After improvements, the bottom of the lake is at 57,4 m with water level at 58,75 m, and the highest point is at 105 m. It is interesting to note that the design's signature feature, the island with the Tempietto, stayed more or less constant at an elevation of 90 m.

Application and practice

For Alphand the raw survey data for the existing site served as the predicate for design strategies and decisions which demonstrate his dual approach as «an engineer with the talents of an artist (Pinckney 47).» In fact, he believed that to progress with a design, «il faut perfectionner les méthodes et introduire l'exactitude dans les procédés empiriques. C'est le seul moyen de relever l'art des jardins, beaucoup trop délaissé et trop méconnu de

nos jour.» (Alphand 1984, XLVI) Reshaping the features of the quarried land entailed large-scale manipulation of the earth, and the final designed landscape resulted from the careful placement of tons of imported rock and soil. Alphand's compilation of the design drafted over the existing conditions enabled him to make detailed estimates for demolition, construction, and specifications. His published map demonstrates what I believe is the first codified techniques for using contours to proceed with design and construction, a commonplace practice today.

This was especially true for calculating «cut and fill.» In this process, by comparison of the contours in section Alphand could determine what areas of the site would either need to have soil and rock removed or added and filled out with new topsoil. These calculations effectively provide a volumetric description of the earthwork providing amounts of rock and earth to be removed or placed in locations of the site to accomplish the final topographic relief desired for the overlay of plants and circulation. This process allowed him to quantify the amount of various materials needed and prepare a cost estimate for building the site that could take into account the prodigious extent of the earthwork and imported topsoil. Quantities were documented in *Les Promenades*, as was the cost of 2.465.769 franc for earthwork phase of the construction. (Alphand 1984, 198–204, 232)

Alphand also used the survey of the existing conditions to inform design decisions ranging from the mundane to the exhilarating. Basic applications of the contour information insured that road and promenade access points connected smoothly into existing perimeter conditions. Study of the contours and elevations also allowed Alphand to shape the land in ways that let him calculate the gradients of the slopes for walkways and roads that resulted in routes blessed with fluid, easy passage on the steep site. It also let him define areas for the requisite «rugged» paths and passages that enhance the varied experience of the park. Finally, it allowed for accurate civil engineering calculations for the retaining walls around the depressed track for the Chemin de Fer de Ceinture and the retaining wall supporting the overlook along the rue de Vera-Cruz. Alphand's deep understanding of the site conditions also supported the creation of exhilarating and sublime moments in the park, especially the development of the series of panoramic highpoints, the much cited grotto and the central island surmounted by the Tempietto. His analytical approach to design and the results thus generated suggest that, «En ce sens, les Buttes-Chaumont, le plus beau jardin de Paris, n'en demeure pas moins, avant tout, un tour de force de technique (Choay 94).»

Significance

Alphand's influence was felt almost immediately in the realm of landscape theory and design in France. In *L'Art des Jardins* (1879) Edouard André clearly draws from Alphand in a number of areas. In a chapter devoted to «Travaux d'execution. —Terassements», he described the surveying and earthworks process, calculations and estimating of costs and lines item expenses for earthwork. (André 406–436) The image of a page excerpted from his treatise depicts some of the techniques and practices of surveying a site further suggests far reaching effects of Alphand's technical approach in the discipline of landscape architecture.

The scope and approach of Alphand's work also extended beyond France via two key mechanisms: travel guides and visitor's comments on the park and, more definitively, through the distribution of *Les Promenades*. The catalyst for both was the 1867 Exposition Universelle; the park shared opening day, a place in the program, and an audience. In fact, *Les Promenades de Paris* was widely distributed throughout the Exposition armature to distinguished heads of state and major cities in Europe and United States. Its influence on urban design and the design process has been recognized in cities from Stockholm and Vienna to Boston and Cleveland in the United States.

For the case of the Buttes Chaumont, the communication of French technical élan and skill was conveyed not only in the park itself and the documentation of the work, but also in the delineation and reproduction of the images in *Les Promenades*. Recall that the landform was mapped in two matched scale plan types —one a technical map, the other a rendered plan. They are the only such pair in Alphand's treatise, suggesting their value. Further, the lithographic technique employed to show before and after contours on the same map is the ONLY two-

color image in *Les Promenades* aside from color botanical plates. This highlights not only the data but also the skill of the delineator, A. D. Fath and the sophisticated printing process that reproduced it. All are part of the emphasis on areas of French technological expertise.

In addition, there is the skilled work of E. Hochereau, the delineator of the rendered image of the park in plan view. Hochereau maintained the scale as well as the orientation of the contour map with north at the bottom. Thus, the shadows indicating the topographic relief are correctly cast with the sun from the southeast, rather than in the precision method established by Dufour. Additionally, this direction better highlights the dramatic highpoints and structure of the park. What has been gained is a descriptive veracity that sets this plan into the system of survey accuracy informing the partner plan of before and after contours.

Conclusion

Through fully documenting his technical mastery and itemizing the materials and means of production for his works in *Les Promenades*, Alphand distinguishes his work and the goals of the Second Empire. It is imperative to realize that his maps and images of the Buttes Chaumont from Les Promenades are NOT ideologically neutral — they are effectively an action, a perspective of the city and the site at that time which reflects a relationship between maps and forms of knowledge and power. (Harley 105–106) Rendered and published in a way that celebrated the technical production of the park, the contour and rendered plans are in effect projections, figured renditions of a technical vision. The emphasis on the site's topographic attributes proclaimed an ideological mastery over the physical surface of the earth. This message was an essential tactic in Napoléon III's agenda to proclaim the sovereignty of the convergence of art and industry in the redesign of Paris.

Notes

1. The Verniquet survey appeared on the «Plan de Guillot, 1775», Centre Historiques des Archives Nationale, Paris. The cartouche in the upper right corner of the Guillot plan shows, among other things, cherubs pointing to France on a spinning world globe with charts and maps below it cherubs unfurling a chart of geometric figures and diagrams. Directly above the title, a tempietto of ionic order atop a small rocky, mount from which rays of light emanate. The map just begins to include the area of the future Parc des Buttes Chaumont, and it clearly indicates the buttes as a quarried landform. See also «Plan de la Ville de Paris avec sa nouvelle enceinte, Levé Géométrique sur la Méridienne de l'Observatoire par le Citoyen Verniquet, parachevé en 1791», Centre Historiques des Archives Nationales (Paris).
2. Author's translation: «L'étude d'un relief est une opération très-interessante et très-délicate: car elle doit imprimer aux mouvements du sol une certaine grâce, former ou corriger la direction des vallées et des plantations et des plateaux, c'est-à-dire arrêter l'assiette du paysage. C'est l'opération fondamentale don't tout le rest dépend.»

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Survivors amongst the rubble: Traditional timber-laced masonry buildings that survived the great 1999 earthquakes in Turkey and the 2001 earthquake in India, while modern buildings fell

Randolph Langenbach

The Kocaeli and the Bhuj Earthquakes in Turkey and India were devastating disasters, with vast destruction of buildings and countless deaths and injuries in both urban and rural areas. One particular problem unique to urban areas was dramatically illustrated in the recent Bhuj Earthquake when, in the town of Anjar, several hundred school children participating in a Republic Day parade were killed while standing *outside* the buildings. This tragedy occurred because the walls of the surrounding buildings collapsed outward into the narrow street where they were standing, from which there was no escape.

The Bhuj Earthquake devastated older masonry buildings and newer reinforced concrete buildings alike. In Bachau, the entire city was effectively wiped out, with nothing left undamaged and little even left standing. However, in the nearby city of Ahmedabad, and also in 1999 earthquake damage districts of Turkey, the profiles were very different. In Ahmedabad, where the older masonry houses were constructed with timbers in the walls, all survived the Bhuj Earthquake with little damage and no collapses, while a significant number of new apartment blocks collapsed with a high death toll. In the Marmara Region of Turkey after the devastating 1999 earthquakes, hidden among the many heavily damaged or collapsed modern buildings were many older timber and masonry buildings that, with few exceptions, survived with very little damage.



Figure 1
View of Anjar City Center after the Bhuj Earthquake of January 26, 2001

Did historical earthquake threats influence the invention and evolution of the timber-laced construction types, and if so, why is there such a wide discrepancy between the construction and performance of the buildings around Bhuj and those in the Walled City area of Ahmedabad? In addition, why did these seemingly weak and vulnerable older buildings prove to be safer than many of their more recent reinforced concrete neighbors? What the recent earthquakes in Turkey and India have shown is that the development of modern strong materials and the greater sophistication in engineering design have not always resulted in safer structures, as it was the *modern* buildings in both India and in Turkey that often proved to be more vulnerable than traditional forms of construction practiced for thousands of years.

Timber-laced construction can also be found in both Spain and Portugal. In Madrid, many of the buildings in the historic central area around the Plaza Major which appear today as solid masonry buildings underneath a layer of stucco are, in fact, composed of walls of timber with brick or rubble stone masonry infill (Figure 2). Many of the buildings in Lisbon that were rebuilt after the great Lisbon earthquake of 1755 were constructed with heavy timber frames imbedded in the masonry, in this case a deliberate response to the earthquake risk. In fact, the Lisbon example may have been based on observations of earlier timber-laced buildings that may have done comparatively well in the earthquake, thus encouraging its more elaborate use for earthquake hazard mitigation during the reconstruction.

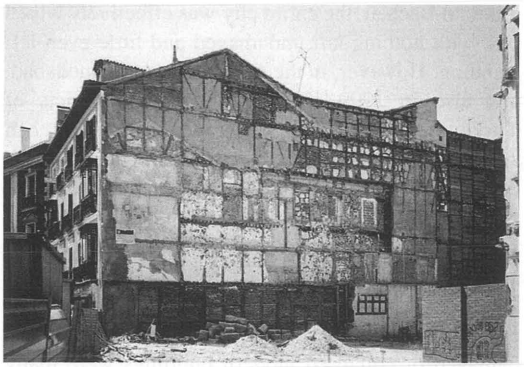


Figure 2
Timber and masonry infill-frame construction near the Plaza Mayor in Madrid

Historical Background

Timber-laced masonry can be divided into two sub-categories: timber-frame with infill masonry (infill-frame),[1] and bearing wall masonry with horizontal timber-lacing (laced bearing wall). These two types were often used in the same building, with the laced bearing wall system used for the ground floor and the infill-frame for the upper floors. Variations on these types of construction can be found across the broad, seismically active belt that extends around the globe from Africa and Europe across Asia to Central America. Rather than earthquakes per se, the circumstances that led to the survival of these buildings are likely to be the successful byproduct of technologies developed as much for their economy as for their strength. However, the recent earthquakes in Turkey and India provide an opportunity to compare the performance of the two types of timber-laced masonry construction with that of masonry buildings without timber-lacing, as well as with the performance of modern buildings constructed of reinforced concrete.[2]

Infill-Frame Construction

Because it is rare for the wooden armature of these sorts of buildings to survive as archeological ruins, the chance of finding ancient examples of the infill-frame construction type is low, but the unique burial under volcanic mudflows, and the modern-day archeological uncovering of Herculaneum in Italy has provided the unique opportunity to peer back through 2.000 years and find early examples of this type of construction (Figure 3).[3]

Because of its economy and ease of construction, it is probably safe to assume that infill-frame construction became widespread throughout Europe from an early period. Timber-with-brick-infill vernacular construction is documented to have first appeared in Turkey as early as the eighth century (Gülhan and Güney, 2000). One hypothesis is that the building tradition traveled from Europe into Asia as a result of the reach and influence of the Ottoman Empire, which at one time extended almost from Vienna to the Caspian Sea.

Today, variations on this type can be found in almost every part of Europe, including England and Spain, as well as Asia. It also can be found in Central America, and can even be found in the United States in New Orleans, a city of French origins, in some other historic French settlements on the Mississippi, and in parts of Pennsylvania, where it has been derived from the German *fachwork*.

Laced Bearing Wall Construction

Laced Bearing Wall construction may have had its origins in ancient times as well, although it is not so identified in Vitruvius' work. An even earlier



Figure 3
Pre-79AD Infill-frame construction found and restored at Herculaneum

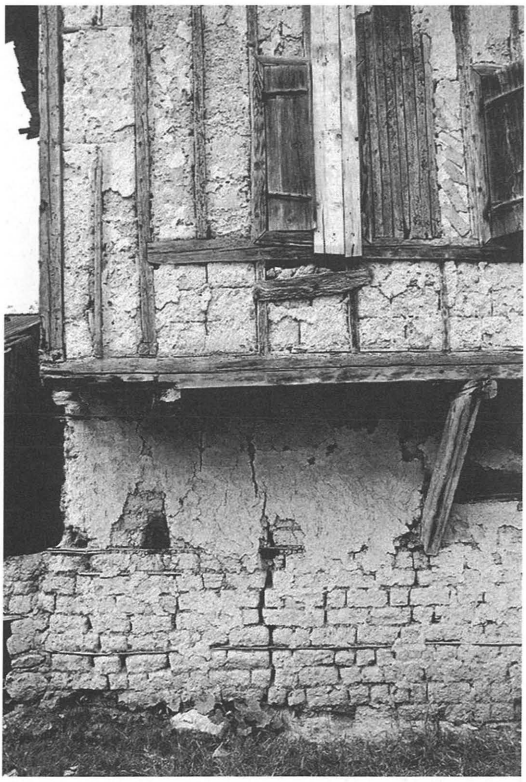
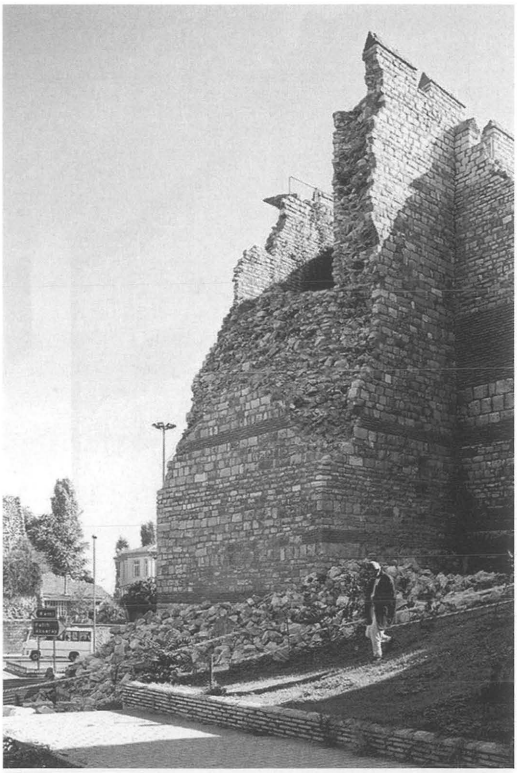


Figure 4
View of Infill-frame construction in the historic Ottoman town of Safranbolu, Turkey

example has been identified at the Minoan «New Palace» of Knossos, dated 1450BC (Kienzle, 2002). It may also be loosely related to the utilization of horizontal bands of wide and flat Roman brick that was sometimes laid at intervals into walls composed of more random mortared masonry. At Pompeii, a number of the piers between storefronts were reconstructed with brick bands, and this construction may have been part of repairs of damage from an earthquake that occurred 17 years prior to the volcanic eruption that buried the city. This same type of construction can be found in Istanbul most notably in the medieval city walls, where the belts of red brick are an integral part of the architecture —so much so that when modern restorers reconstructed a section of the walls, they applied the brick band as a thin layer on the surface, rather than as a structural layer extending through the masonry. Interestingly, it was only this newly constructed section that collapsed when the tremors which radiated out from the distant August 17, 1999 Marmara earthquake reached Istanbul. The far more deteriorated portions of the wall where the brick bands remained in their original form remained standing.

Some of the most elaborate examples of laced bearing wall construction can be found in Srinagar, Kashmir, where this type of construction, referred to as *Taq,* is the predominant historical vernacular type. Here the type evolved to allow building of structures onto soft waterlogged banks of the alpine lakebed in the Vale of Kashmir, where the heavy masonry structures were subjected to differential settlement. Here the heavy timber beams are laid in only horizontally, with the masonry carrying all of the





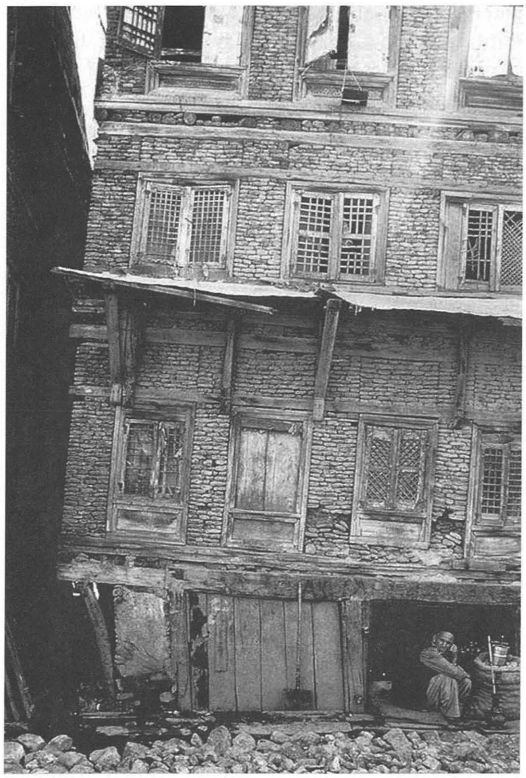
Figures 5 and 6
Istanbul City walls showing brick banding in surviving historic section and collapsed reconstructed section with fake banding

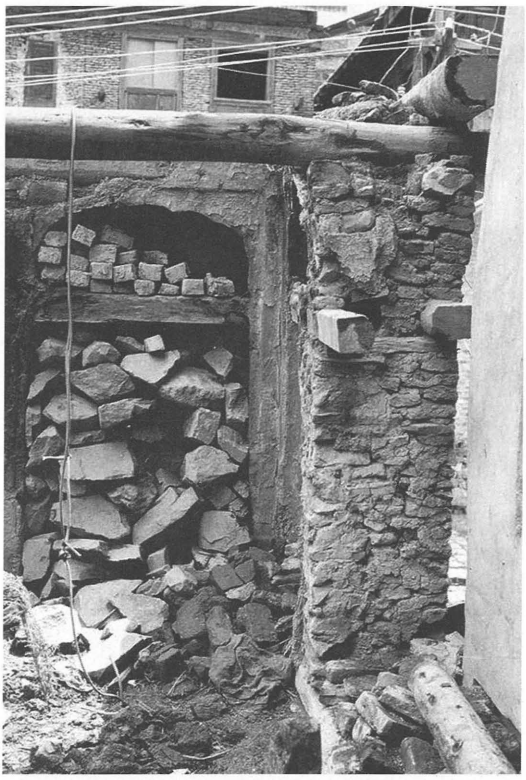
vertical loads. The timber bands, which resemble ladders laid into the walls, run both above and below the window frames and at each floor level, where the joists extend through the wall and are secured to the wall by the timbers laid below and above them, which are themselves surmounted by the weight of the overburden of masonry of the floor above or the parapet under the roof.[4]

The Ottoman Method of Construction in Turkey

In Turkey, and also in Greece, houses were often designed with the laced bearing wall construction on the ground floor level, and the infill-frame used for the upper stories. The thicker, often windowless, bearing walls served to enclose the storage or barn area of the structures, with the lighter more open infill walls above enclosing the living quarters. The Turkish Ottoman-style house, with its tiled roof and overhanging timber-and-brick bays above a heavy stone first floor wall, has become an icon known worldwide. Where they survive, the overhanging upper stories, or jetties, contribute to the visual vitality and delight of historic Turkish towns. The jetties strengthen the buildings because the joists that cantilever over the walls below hold those lower-story walls firmly in place with the help of the weight of the infill masonry overhanging upper story. This compressive force gives the heavy walls below added strength against lateral forces.

The upper story is almost always constructed with the infill-frame type of construction, with the frame





Figures 7 and 8
Taq construction in Srinagar, Kashmir and demolished section of wall showing timber lacing in wall section

infilled with a single-withe of fired brick or stone masonry. This type of construction is referred to in Turkish as «*hımı_*» (pronounced «humush»). This construction utilizes a weak mortar of mud or lime holding a single wythe of masonry into a timber framework of studs rarely more than two feet (60 cm) apart. The studs are themselves tied at mid-story height by other timbers. Because the masonry is only one withe in thickness, the walls are light enough to be supported on the cantilevered timbers.

For those houses where the *hımı_* style rests on the heavy load bearing masonry base, the multi-wythe masonry bearing walls of the first story, are often laced with horizontal timbers, —in Turkish, the timbers are «*hatıl* (s) *hatıllar* (pl)»—. In contrast to those used in Kashmir, these are often very thin timber boards laid into the wall at vertical intervals of about 3 feet (1 m). They are placed so that they overlap at the corners. They thus serve to bind the stone layers together without interrupting the continuity of the masonry construction. In those regions most affected by the 1999 earthquakes, however, the bearing wall type was rare. There, the houses were of *hımı_* construction from the ground up, thus the discussions of earthquake performance of the timber-laced construction as witnessed following the recent earthquakes in Turkey and in India will be focused primarily on this type.

The Marmara and Düzce Earthquakes

The Marmara earthquake (also called the Kocaeli earthquake) of August 17, 1999 killed approximately thirty thousand people.[5] The epicenter was just 200 kilometers east of Istanbul. In some areas of Gölcük

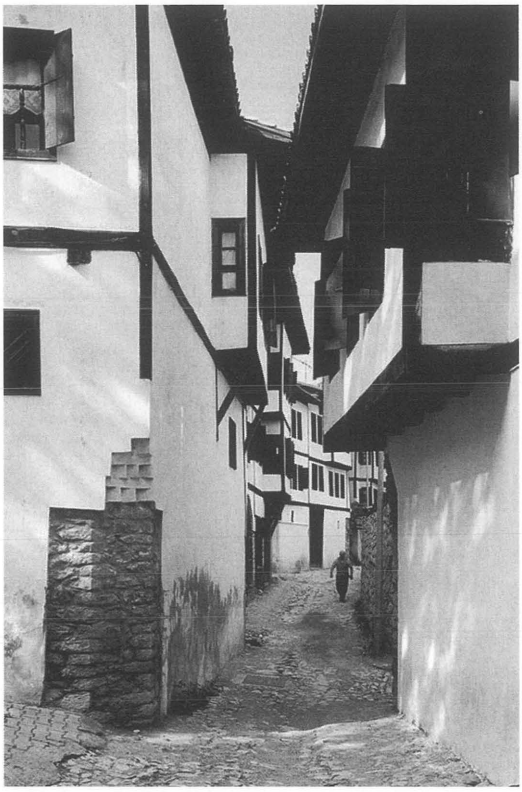


Figure 9
Traditional Ottoman style Turkish architecture in Safranbolu, Turkey

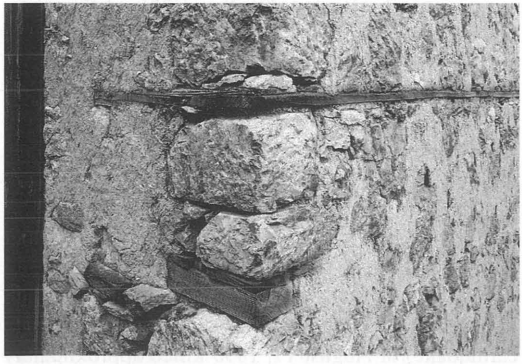


Figure 10
Laced bearing wall in Safranbolu, Turkey

and Adapazari, the earthquake destroyed more than a third of all housing units, almost all of them in reinforced concrete buildings.[6] There were clusters of *hımı_* buildings in the heart of these districts. These houses, mostly dating from the early part of the twentieth century, pre-dated the ruined reinforced-concrete apartment blocks nearby. Many of the older *hımı_* houses remained intact, but a few were heavily damaged. This finding was confirmed by two Turkish professors who conducted a detailed statistical study in several areas of the damage district who found a wide difference in the percentage of modern reinforced concrete buildings that collapsed, compared to those of traditional construction (Gülhan and Güney 2000).[7]

In one area surveyed in Adapazzari a single *hımı_* house collapsed, killing an occupant —a rare occurrence of a death caused by the collapse of *hımı_* construction. Decayed timbers could be seen in the ruins. It was the partially damaged traditional buildings here and in Gölcük provided evidence of how this type of construction responded to earthquake forces. Once each building was inspected, and the damaged area in each building identified, a pattern began to emerge. Of those inspected where structural damage was found, most of the damage was concentrated at areas around rotted timbers. Interviews with residents often revealed that the buildings with the most timber decay had been unoccupied for years. It appeared that decayed timber significantly degraded a buildings' performance in earthquakes. In occupied houses, the most severe damage resulted mainly from alterations and modernization work that had corrupted the integrity of the original frames and walls.

Inspecting the interiors of some of the houses provided a more complete understanding of the behavior of *hımı_* as a structural system. It was evident that the infill masonry walls responded to the stress of the earthquake by «working» along the joints between the infilling and the timber frame; that is, the straining and sliding of the masonry and timbers dissipated a significant amount of the energy of the earthquake. The only visible manifestation of this internal movement was the presence of cracks in the interior plaster along the walls and at the corners of the rooms, revealing the pattern of the timbers imbedded in the masonry underneath. This level of damage was evident in every house. On the exterior,

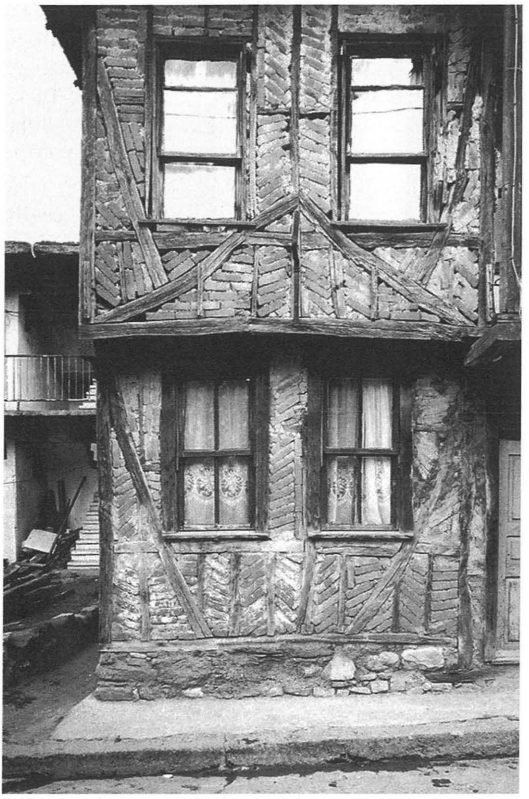


Figure 11
*Hımı_* house in Gölcük after earthquake constructed in 1955. There was only slight damage to the interior of this house

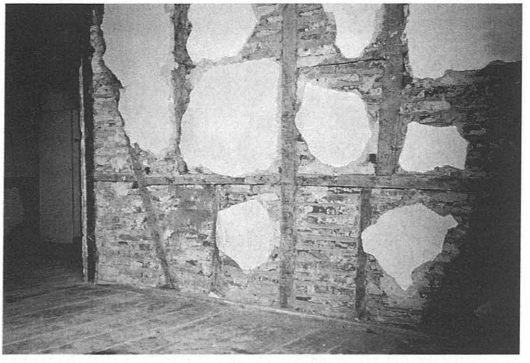


Figure 12
Hımı_ interior wall in Düzce after earthquake

unless the house was stuccoed, damage was impossible to see. The bricks themselves were only infrequently displaced sufficiently for a crack to be visible. The movement was primarily along the interface between the timbers and the brick panels rather than forming a crack within the panels themselves.

The typical *hımı_* construction does not have mechanical ties between the timber and masonry to hold the infill masonry in place. As a result, in some cases, small sections of the infill were shaken out from between the studs near the top of the upper-story walls. Because of the existence of the timber studs, which subdivided the infill walls into small panels, the loss of portions or all of several panels did not appear to lead progressively to the destruction of the rest of the wall. Many walls were missing some of their infill, but evidence of «X» shear cracks, so common in the infill in the modern reinforced concrete buildings, was non-existent in the *hımı_* structures. The closely spaced studs reduced the likelihood of the propagation of «X» cracks within any single panel. In addition, the subdivision of each structural bay with a tight network of vertical, horizontal, and diagonal timbers, rather than vertical studs alone, appeared to have been successful in reducing the possibility of the masonry falling out of the frames.

An important additional factor in the performance of the walls was the use of weak, rather than strong mortar together with bricks that are stronger than the mortar. The mud or weak lime mortar tended to encourage sliding along the masonry bedding planes instead of cracking through the masonry units when the masonry panels deformed, reducing the contrast between rigid masonry panels and the flexible surrounding frames.

Strength versus Capacity

This pattern of damage helped explain why these buildings were capable of surviving a major earthquake that had felled modern reinforced-concrete buildings. The basic principle in this weak, flexible-frame-with-masonry-infill construction is that there are no strong and stiff elements to attract the full lateral force of the earthquake. The buildings thus survive the earthquake by not fully engaging

with it. This «working» during an earthquake can continue for a long period before the degradation advances to a destructive level.

While these structures do not have much lateral *strength*, what they possess is lateral *capacity*. These buildings respond to seismic forces by swaying with them, rather than by attempting to resist them with rigid materials and connections. This is not an elastic response, but a plastic one. The swaying and deformation of these structures is different from that of a tree, the suppleness of which allows it to bend elastically. When these structures lean in an earthquake, they do so with incremental low-level cracking which is distributed throughout the wall by the interaction of the timber structural elements with its confined masonry infill.

This controlled damage is what the «working» of the structure means. It is how a building made with a disparate assembly of brittle materials is able to survive seismic forces that are far larger than could be resisted by it in a fully elastic undamaged state. In other words, although the masonry and mortar is brittle, the *system* —rather than the materials that make up that system— behaves as if it were «ductile».[8]

In addition, by dissipating energy, the «working» also affects the natural frequency or «period» of the vibration of the structure. Resonance with earthquake vibrations is a principal factor in the cause of earthquake damage to buildings in general. The controlled sliding and cracking of the infill masonry reduces the infill-frame structure's ability to resonate with the earthquake by providing damping, just as a shock absorber does for a car. In contrast to this, there are many examples of modern structures that were strong enough to resonate elastically at ever increasing amplitude until the catastrophic failure of a critical structural member caused their sudden collapse. Simply stated, all of this is the difference between *strength* and *capacity*.

The Orta Earthquake of June 6, 2000

Ironically, it was a much smaller earthquake that followed the 1999 earthquakes in Turkey that has provided one of the best sources of data from which to evaluate the capacity for earthquake resistance of the construction, compared to that of the standard



Figure 13
Interior of *hımı_* house in Orta after earthquake showing damage to mud and lime plaster over infill walls

low-quality concrete construction. This smaller earthquake occurred six months later, in June, 2000, and was centered on the village of Orta, north of Ankara. It measured only 5,9[9] on the Richter Scale and thus was small enough to escape international attention.

In this earthquake, many *hımı_* houses did suffer widespread cracking and shedding of plaster and stucco, and a few had damage to the infill masonry. This level of damage was hard to explain when compared to that found in the infill-frame houses subjected to the full brunt of the Marmara earthquake, where the shaking was stronger and continued for a longer period. The *hımı_* houses in Gölcük and Adapazari had about the same level of damage as the Orta houses. This stands in sharp contrast to the performance of the reinforced concrete buildings. While in Orta the reinforced concrete buildings were only lightly damaged, in the Marmara and Düzce earthquake area vast numbers of them suffered heavy damage or collapse.

What can explain this discrepancy between the performance of the infill-frame buildings and that of reinforced concrete in the two earthquakes? To look for an explanation for this phenomenon, it is valuable to compare the Marmara and the Orta earthquakes with each other. The modern reinforced-concrete buildings went from performing well in the moderate seismic event in Orta to being lethally dangerous in the larger event, while the traditional houses did not. Thus the minor cracks seen in the reinforced concrete

buildings in Orta may in fact be the onset of damage that, in a larger event, might have led rapidly to the collapse of the buildings.

This observation is underscored by the fact that many of those buildings in Düzce that were *damaged* in the August 17, 1999 Marmara earthquake, *collapsed* in the November 11 Düzce earthquake. This observation is significant in that it indicates that, only at one's peril, could one draw conclusions about a building's performance from observations of a single earthquake taken in isolation —particularly a moderate one like that in Orta in a seismic zone capable of producing a large one.

By comparison with the ordinary and often poorly constructed modern Turkish reinforced-concrete housing blocks, the traditional infill-frame structures demonstrated a greater ability to sustain a long duration of severe shaking without progressing much beyond the level of damage sustained in the more moderate Orta earthquake. Thus, the fact that the traditional buildings suffered a level of damage that was similar in both the larger and the smaller earthquakes serves to illustrate their ability to survive massive earthquake shaking, despite the fact that damage begins to occur at lower levels of shaking than it does in reinforced concrete structures.

Lessons from the Past for Modern Reinforced Concrete Construction

The shift from traditional low strength materials to reinforced concrete is a radical transformation of the entire building construction process that has affected many regions of the world. Reinforced concrete is an industrialized high-tech material that is safe and strong *only* when it is used in a way that shows knowledge and respect for its properties. And indeed, therein lies the problem. In many countries where this method of construction now predominates, it is subjected to a low-tech building process not unlike that used for the vernacular masonry buildings it has now displaced. When misused, it is dangerous —as the recent earthquakes have so tragically shown.

The most common form of reinforced concrete structural system now used in most places is the moment frame with masonry infill walls. In contrast to shearwall buildings, the moment frame relies on the strength of the beam/column intersections to resist deformation and collapse in earthquakes. The most significant problem with this form of construction is that a failure to provide for sufficient strength or ductility in the frame joints can lead rapidly to collapse in an earthquake.

The infill walls in modern reinforced concrete construction generally have strong mortar binding weak masonry units, and these masonry walls fill each structural bay without intervening studs. In Turkey, the most common infill for the interior partitions and exterior walls is a lightweight hollow clay block that has barely more strength than a dinner plate. In India, commonly it is a low temperature fired brick that performs better than the Turkish material, but none-the-less it can crumble easily.

Rarely is the infill considered in the engineering design process as part of the lateral resisting system, and it is often ignored in calculations. In spite of this, the masonry infill does play a significant role that sometimes can help to save a building that has weakened joints. More often, however, it can contribute to the collapse of a building because its rapid degradation in specific areas can transfer concentrated loads onto localized parts of the frame, which are then overwhelmed. As can be seen in Figure 14, these infill walls can readily collapse completely when an earthquake distorts the building's frame. Sometimes, to avoid damage to the surrounding reinforced concrete frame from the «diagonal strut» effect, where the stiff infill causes a corner column to break, leading to collapse, the infill material is sometimes deliberately separated from the frame.



Figure 14
Collapsed interior infill wall in reinforced concrete building in Gölcük

While the infill in modern construction has often performed badly, the infill in traditional construction has performed well. What accounts for this apparent discrepancy? Two things may account for this: (1) the subdivision of the infill masonry into smaller panels with horizontal and vertical studs within a single bay of the building's structural frame, and (2) the use of weak mortar with strong masonry units in the traditional infill compared with what are often weak masonry units and cement-based strong mortar used in the modern infill walls.

The principal lesson embodied in comparing the performance of the timber-laced vernacular construction with that of the modern buildings that collapsed in the earthquakes is thus: strength and rigidity are less effective in than flexibility, ductile behavior, and cumulative nondestructive damping. To improve the performance of reinforced concrete infill-wall construction, the lesson from the traditional construction is to make the infill walls act not as shear walls, which they cannot be, but as «cross walls», which they are eminently capable of being. (A «shear wall» is designed to be strong enough to carry to the foundation all of the imparted lateral loads of the building. A «cross wall», which may be only a floor-to-floor partition, is only designed to take loads and distribute them to other horizontal or vertical elements in the overall structural system). They can also serve to dissipate large amounts of energy by cracking in a controlled manner. With the introduction of studs like those found in traditional construction, collapse from shear failure of the entire panel can be avoided because the infill can deflect nondestructively and be restrained from falling out of the frame.

Conclusion

Further research is required to determine whether earthquakes in the past have shaped the form of traditional construction methods. . People surely must have responded to known earthquake risks in the past, but how they did so is very difficult to ascertain. It is logical to believe that earthquakes must have been a factor in the evolution of building design and construction in affected regions. However, at the same time, they may not have been a defining one. The economy and availability of building materials and craftsmanship is likely to have had a stronger influence than the infrequent risk from earthquakes. The infill-frame form of timber-laced masonry was economical in its use of materials and labor. In the case of the timber-laced bearing walls, the use of the timbers was a cost-effective way of giving a rubble stone wall a great deal of added stability when the dressing of the stones was impractical.

Regardless of their historical sources, recent earthquakes have shown that, intentional or not, timber-laced buildings have demonstrated a level of life-safety in earthquakes that was conspicuously absent from many of the more recent reinforced concrete residential buildings. It is not enough to simply explain collapses of modern buildings and their consequential carnage as the result of inadequate design and/or poor construction. As long as reinforced concrete is used ubiquitously in many areas as the default material for ordinary construction, then a large number of the buildings constructed with it should be assumed to be less than well built.

Moreover, earthquake safety is thus not achieved by pointing fingers at builders after earthquakes; it can only be achieved by recognizing that a certain amount of bad construction is inevitable, and looking for ways to mitigate its most dangerous consequences by changing construction practice so that the safety does not depend solely on the quality of the concrete frames. That is where some of the characteristics of traditional construction can provide lessons for contemporary building practice. They have proved that they can survive earthquakes of great magnitude based on structural behavior that is dependent neither on formal engineering nor on sophisticated knowledge of construction through flexibility, energy dissipation, and redundancy.

As we look for solutions to the problems that have been so profoundly thrust on so many by the tragic earthquakes of the last several years, it is important to be open to receiving what the wisdom of the ages may have infused into traditional structures. It is important to realize that the cultural value of indigenous architecture lies in their structural characteristics as well as in their visual image. There is more to traditional buildings than their architectural veneer. Too often what passes for conservation is the reconstruction of buildings in reinforced concrete, with false timbers simply attached to the surface. When it is understood that there are many historical systems from



Figure 15
Collapsed Reinforced concrete building in Gölcük

which we can learn valuable lessons for construction today, then these historical structures take on a meaning that brings them to life in ways that transcend their contribution to style. People have coped with the larger than life forces of earthquakes and other natural disasters long before the invention of strong construction methods in reinforced concrete and steel —and as seen from some of these examples here— they sometimes have been remarkably effective.

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Notes

1. In England, this is referred to as «half-timbered», but to avoid confusion with the specific English version still visible in many surviving Elizabethan buildings, the less regionally specific term of «infill-frame» will be used here. The Elizabethan half-timbered buildings are usually characterized by the use of heavy timbers for the frame, rather than the lighter, more frequently spaced, timbers seen in the Roman, Ottoman and other Southern Europe and Middle Eastern versions.
2. To avoid confusion, the reference to «modern unreinforced concrete» construction here and throughout this paper is focused primarily on the common, largely unregulated, concrete construction of housing and office blocks which fill the earthquake damaged cities and towns. In reporting on the poor performance of these structures, the author does not mean to imply that all structures of reinforced concrete construction performed poorly. As the engineering surveys have established, there were many reinforced concrete buildings that had been engineered and constructed to a high standard, and for the most part, these buildings did perform well in both India and Turkey.
3. Vitruvius, in his description of different wall typse refers to «cracticii» that is thought to perhaps be a description of the construction type found at Herculaneum, but his description for plastering of craticii walls tends to reinforce a conclusion that what he is discussing (as he is quite critical of the craticii as a construction practice) is more likely a wattle and daub-like form of construction. What these passages do illustrate, however, is that the Romans were quite experimental in developing lightweight forms of construction out of less permanent materials than stone and natural cement concrete, but, except for the example at Herculaneum, examples of these have not survived the intervening 2000 years. Different translators have interpreted the term «cracticium» differently. While Ingrid Roland (1999) translated it to «half-timbered» based on the Herculaneum examples, in 1914, Morris Hicky Morgan translated it to «wattle and daub.»
4. For a more detailed description of the architecture and construction found in Srinagar, Kashmir, see Randolph Langenbach, «Bricks Mortar and Earthquakes», APT Bulletin 31: 3–4 (1989).
5. Kandilli Earthquake Research Institute (2000). Web Site, Boğaziçi Üniversitesi, Istanbul, Turkey.
6. *IBID*
7. Gülhan and Güney documented that in one district in the hills above Gölcük of the 814 reinforced-concrete, four-to-seven-story structures, 60 collapsed or were heavily damaged, while only 4 of the 789 two-to-three-story traditional structures collapsed or were heavily damaged. The reinforced-concrete buildings accounted for 287 deaths against only 3 in the traditional

structures. In the heart of the damage district in Adapazari, where the soil was poorer, this research shows that of the 930 reinforced concrete structures, 257 collapsed or were heavily damaged and 558 were moderately damaged, while none of the 400 traditional structures collapsed or were heavily damaged and 95 were moderately damaged.

8. *Ductility* refers to a material's capacity for being bent beyond its elastic range without breaking. In the case of this traditional construction, where most of its lateral resistance is provided by the brittle masonry, the term applies to the behavior of the system, not the materials which make up that system. In the 1981 published paper «*Earthen Buildings in Seismic Areas of Turkey*», Alkut Aytun credits the bond beams in Turkey with «*incorporating ductility to the adobe walls, substantially increasing their earthquake resistant qualities.*» From Proceedings of the International Workshop on Earthen Buildings, Vol. 2 (Albuquerque, 1981), p. 352.1.
9. As reported in the Turkish daily papers the day after the earthquake. The USGS web site reported 6.1.

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History of Descriptive Geometry in England

Snezana Lawrence

History of the Descriptive Geometry in France and its utilisation in the educational system of France since the 18th century, has already been well documented in the work of Taton (1951), and more recently Sakarovitch (1989, 1995). The history of the technique in England, however, makes a captivating story, particularly as it relates not only to the technique itself, or how the treatises relating to it were translated to English,[1] but because it was closely related to the establishment of the architectural profession in Britain.

Invention of Descriptive Geometry in France and its translation to English

The man who both invented a technique on which all the modern graphical communication is based and initiated a fundamental change in the teaching of such subjects was a French mathematician Gaspard Monge (1746–1818). The background to his understanding of mathematical concepts is largely explicable by the general development of mathematical education in France at the time.

The process of modernising education by making it more applicable to industry[2] was to be adopted in Britain only at the beginning of the 19th century. In France, however, this was initiated much earlier: René Descartes (1596–1650) in his *Project d'une École des arts et Metiers* which he submitted in 1638 to d'Albert (1578–1641) the Treasurer-General of France at the time, had already outlined such a concept. As Wolf pointed out:

> The pioneers of modern science . . . wished and expected the relations between science and technology to be most intimate. The notion of knowledge for its own sake had no glamour for them. In fact, it was their great expectation that the new sciences, unlike the old book learning . . . would confer power.[3]

This power was to be seen to be important for its application both to military and civil engineering. Scientific advance was thus regarded as not only a matter of necessity, but also of national security and prestige. Monge was both a «product» of this system of education geared to support practical application of sciences, and in his later life, an avid supporter in further promoting the cause of scientific relevance to the matters of industry.[4] In l'École Royale du Génie de Mézières, where Monge worked as a draughtsman in late 1760s he conceived a new technique of orthographic projection which he called Géometrie Descriptive. This method was naturally related to the methods widely used at the time,[5] but nevertheless offered entirely new view of the projection and a possibility to visualise spatial relationships within an easily conceivable framework of two mutually perpendicular projection planes given only by their intersecting line. The method was examined with the highly critical eye of his superintendents who had

their suspicions about Monge's speed in resolving the problem of defilement of fortification,[6] but when properly understood, his method was accepted as a new technique for solving the problems related to visualisation and design of fortifications. As such the technique was considered to be a potential hazard in terms of national defence —and was immediately ruled a military secret.

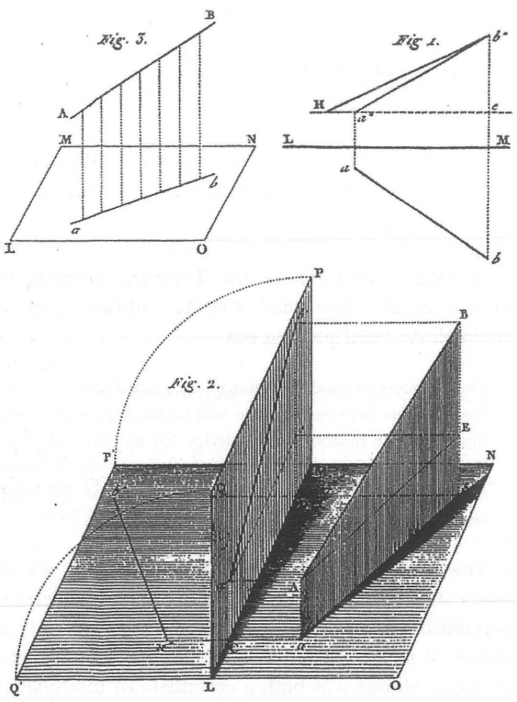


Figure 1
Originally Figure 2 from Monge's *Géometrie Descriptive*, Hachette edition (1811), showing how a line in space, AB, can be defined by its projections onto horizontal and vertical planes, and how, in order to extract measurements, the vertical plane can be considered revolved to lie flat in the horizontal plane. This describes the process of rabatting, or bringing the plane in which a particular length lies into the projection plane, in order to get the real length

The first treatise on the technique was published only after the French Revolution. On the 20th January 1795 (1st pluv.III) at the École Normale, Monge gave his first course in Descriptive Geometry. The text of

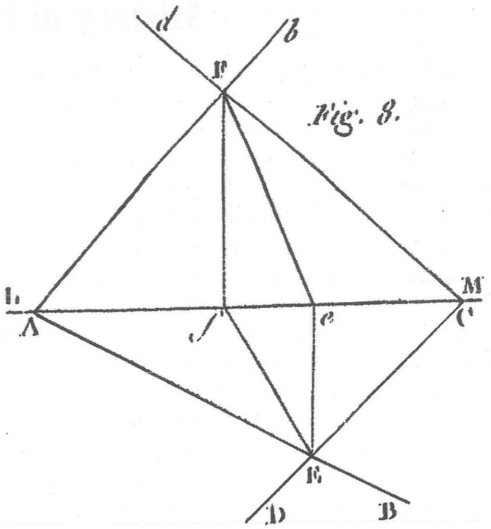


Figure 2
Plate III from *Géométrie Descriptive* by Monge, Hachette edition (1811), showing the primary operations with two planes. The system, although determined by two planes of projection, is actually represented only by their line of intersection AC = LM

this course, which was published soon afterwards, came from the stenographic notes of the lessons given, and these were first published in the Journal of the École in 1795, before being transformed into a book in 1799. The book came out in numerous editions and the technique has been taught in both the schools of France and across the world ever since. England, it is fair to say, is probably one of the few countries of Europe where the technique has not survived the initial interest and translation —in its original form. I will, however, show that Descriptive Geometry did play an important role in initiating a search for a universal system of graphical communication which could be adopted to the needs that were deemed to have existed in England at the time.

Géométrie Descriptive was translated into Spanish in 1803, and into English in 1809, presumably for military purposes, as there are no publications to be found in English libraries to suggest that the work was made public. Nevertheless, as will be shown

later, we now have a knowledge that a number of private copies of translation of the technique were circulating among the artisans and architectural draughtsmen at the beginning of the century.

The lack of interest shown upon the translation of the technique into English is partly due to its having been translated during the period between the Napoleonic wars,[7] so the technique itself was regarded as the invention of one of the most prominent republican educationalists. The competition between the two nations —English and Fren— in matters not only of war but of prosperity and industry during the intervals of peace is an important element to be considered.

The lack of a suitable translation and instruction into the technique by one of the «original» students was another result of the wars in which the French and English were engaged in at the time. Different destiny was to await the technique in the United States of America, where Claude Crozet,[8] one of Monge's pupils, introduced the study of descriptive geometry in 1816. It had not hitherto been taught in the US, and Crozet prepared the first American textbook on the subject. Both at West Point and at the Virginia Military Institute with which he was later associated, descriptive geometry has continued to be taught up to the present time.

Because Crozet actually transferred the technique from first hand experience, and published his own interpretation —a treatise on the subject— his treatment took root. Because there was no tacit, first-hand experience of the technique in England, those aspects of the technique which were not written about in the treatises could not be transferred successfully to the syllabi of the English schools. There was no-one like Crozet who was able to perform a similar service in Britain.

Descriptive Geometry, stone-cutting and mythology of the building craft

It was however, through another door that the Descriptive Geometry would enter the stage of the development of educational system in England and play an important role in the development of the graphical communication related to architecture. As previously mentioned, various methods of graphical operations which were incorporated into the system of descriptive geometry were already written about in works published since the first half of the 17th century both in England and in France.[9] The records exist which point that Monge was aware of this connection and taught descriptive geometry at Mézières in conjunction with the practice on stone-cutting. J. B. Meusnier (1754–1793), one of Monge's most gifted pupils at the school of Mézières, wrote on the subject in 1777, expounding the method of Monge, and said:

> Instead of making dull details of the stereotomy, our lectures . . . practice the use of the principles involved in the cutting of stones.[10]

It was here, in seeing the origin of and the application to the stone-cutting, that Descriptive Geometry attracted interest from the architectural educationalists in England. The reason for this interest was related to the interwoven tapestry that the architectural professional establishment in England had become by the 19th century, a cross between profession and mythology related to stone-masons craft, which, in turn, was closely related to Freemasonry, an entirely English invention.[11]

Freemasonry grew in London and was officially instituted some fifty years after the Great Fire of 1666. The Great Fire of September 1666, in the City of London, destroyed the old St. Paul's Cathedral, 87 parish churches, and about 13,000 houses.[12] Apart from destroying much of the physical structure of London, it also destroyed some of its social configuration. This was particularly apparent in the effect it had on the system of the building guilds which formed the Masons' Company of London. As Colvin (1978) has shown, until 1666, the system of masons' guilds had an elaborate system of trade control over the whole of the region for which it was responsible. After The Great Fire, however, as the need for labour in rebuilding the city far exceeded that on offer, the system of trade control and especially the system of entry to the trade, had to be relaxed in order to attract and maintain a sufficient number of skilled workers involved in the process of rebuilding.

As a result of this relaxation, the monopoly which the building guilds had effectively maintained since their institutionalisation in the second half of the 14th century, and which controlled the entrance to the building trade, quickly crumbled, and was never

successfully restored. In order to attract the much-needed workforce, Parliament passed an Act which gave permission to all foreigners working on rebuilding the city of London to remain in the capital and practice the craft. If they did so over a period of seven years, they would enjoy the same liberty as «freemen» of the London Masons' Company for the rest of their lives.[13]

One of the aspects of the historical importance of the Company is based on the somewhat elusive story about the system of initiation which, it has subsequently been claimed,[14] was subsequently taken over by Freemasons.[15] That the various Masons' Companies and their associated lodges existed to provide professional services and institutional control for their members practicing the trade of building («operative masons») is well established.[16] The later Freemasonic lodges, however, whilst employing terminology of operative masonry and architecture, existed to meet, inter-alia, the philosophical, theological or spiritual needs of a membership which was «non-operative» or «speculative».[17]

The myth of continuity of the ancient wisdom related to Geometry and Architecture and the relationship between the divine architecture (of the cosmos) and earthly architects, was invented, defined and publicised by the Masonic establishment with the first edition of the *Constitutions of Freemasons* published in 1723 in London.[18] It shows how Freemasonry claimed to be the natural and contemporary heir to the hidden wisdom as all the elements were successfully assembled together in Masonic ideology: building, geometry (Great Geometer) and the associated secrets. Stone-cutting was, through this association with the Divine Geometry and the Great Geometer elevated from a technique used within a profane craft to a technique whose applicability could be contemplated upon; the principles of stone-cutting and all the mathematical concepts employed became imbued, within an ethical, or even theological context, with a spiritual significance.

When, at the beginning of the 19th century, Descriptive Geometry was translated into English, the concept of the building lodge was almost non-existent and in its place were cooperatives of craftsmen lead by an architect. This developed from the practice introduced in the 18th century which was strongly influenced by the Palladianism and the Italian



Figure 3
An engraving published in 1734, showing a «Master-Mason rare, Whose mystic Portrait does declare, The Secrets of Free Masonry . . . ». It shows the main symbols of Freemasonry and their applicability to initiates' life philosophy. United Grand Lodge of England collection.

Renaissance. In this context the architect was a designer par excellence, and the craftsmen became interpreters of the design and mere executants (in contrast to the building lodge where the Master Mason was more of an arbitrator for the lodge). This development could be best illustrated on the example of Sir Christopher Wren (1632–1723)[19] who worked with a group of architectural craftsmen, and developed an elaborate standard of elements which became an easily identifiable vocabulary for the language of communication. There were mainly two ways in which the design of the building was conveyed to the builders:[20] while for some buildings Wren made elaborate designs, for many he merely

«gave a model» which was interpreted «in the ordinary language of the London builders». In the context of Freemasonry however, the efficient system of communication which Wren developed with his group of builders was thought to have mystical origins. Thus immediately after Wren's death Masonic publications began claiming his membership of the Fraternity, and his membership persists to be a subject of discussion of some importance among Freemasons, although there are no proofs to support the claim.[21]

Architectural schools in London and Descriptive Geometry

When the first two architectural schools —one at the University College London and one at King's College London, were founded in 1841, the first comprehensive manual on Descriptive Geometry was published. No complete work on the subject appeared in English until then, but in 1841 Rev. T. G. Hall of King's College, London, published *The Elements of Descriptive Geometry, chiefly designed for students in Engineering*, which mentioned Thomas Bradley as the first one to give lectures on Descriptive Geometry, at the Engineering Department of King's College in London, during the 1839–1841 sessions. These lectures were also part of the syllabus of architecture at the same school. Hall's —as indeed Bradley's— use and description of the technique, however, was only a summary of what had already been published in other countries on the subject, most notably in France.

The technique began to be taught in its original form, but failed to attract any real following. A claim was made by Hall (1841) and later by Heather (1851),[22] that if only a representation of the final solution or design was more pictorial, the technique would be suitable to the English way of presenting and teaching space. It was deemed to be an abstract technique, difficult to grasp and of little value to the English in their efforts to establish a universal language of graphical communication across the syllabi of the engineering and architectural professions. In fact, the purpose of Descriptive Geometry was never to provide a final pictorial image in a geometrical form. Instead, its aim was to take the user through the method through which the given geometrical form was to be generated. This was however, seldom made clear enough in the treatises which appeared in English language, and even when it was, it was not considered to be an acceptable teaching tool. Quarter of a century after the publication of Hall's work, Cunningham (1849–1919) who wrote on the history and importance of Descriptive Geometry in 1868,[23] established that the terms «plan and elevation» are erroneous in the case of Descriptive Geometry. His view was that

> it is impossible to express the co-ordinate relation of the two planes of projection in such terms as Plan and Elevation, which involve the special ideas —«horizontal» and «vertical».[24]

Instead, Cunningham suggested the use of word «rabatting»[25] which refers to pulling the plane of projection to the plane of drawing. The orientation of planes in descriptive geometry was more of a mathematical task —i.e. the aim was to gain insight into the ways objects are generated, to enable the practitioner to execute particular graphical operations and to discover the precise measurements of the finished object. It was not a representational technique, and this was one of its major drawbacks and one which brought it the name of an «abstract» technique.

During the twenty years or so before the publication of Hall's work, and during the time when the establishment of the architectural profession in England was very much the talk of the day, other techniques were investigated and publicised, some of which had no relation to the methods used in Descriptive Geometry, or indeed, architecture. Such was Isometrical Perspective of William Farish (1759–1837), who, as professor of Natural Philosophy at the University of Cambridge, held lectures on mechanical principles of machinery used in manufacturing industries, for which he often used models which exemplified particular principles. Storage of models and their transport from the store room to the lecture theatres posed a problem, which Farish solved by making the models from elements which were then assembled by his assistants. In order to provide an explanation how these elements were to be assembled, Farish devised a system of graphical communication, which he called «Isometrical

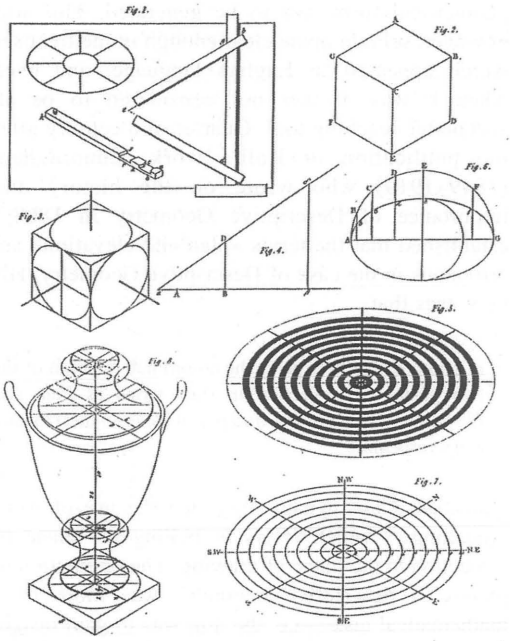


Figure 4
The first page of Farish's treatise on Isometrical Perspective published in 1820

Perspective», in which drawings showed how the machinery was to be built.

The «British System of Projection»

The technique which came to be known as «British System of Projection»[26] incorporated some of the principles of Descriptive Geometry and was closely linked to the practice of stone-cutting. Its inventor was Peter Nicholson (1765–1844), who regarded himself to be both architect and a mathematician.

Nicholson was born in Prestonkirk, East Lothian (Scotland) on 20th July 1765, a son of a stonemason. Nicholson's family background is of great consequence both to his career and our story. Freemasonry in Scotland was, in the late 18th and early 19th centuries, fundamentally different to that in England. Fully operative lodges, which nevertheless practiced the ritual —or speculative Freemasonry— persisted in Scotland up to the middle of the 19th century, although in England this ceased to be the case shortly after the founding of the Grand Lodge of England in 1717.[27] By this date (i.e. 1717), the two concepts —that of operative masonry and speculative, or ritual, Freemasonry— were strictly defined in England, and masonic, or building lodges, were no longer involved with speculative, or philosophical Freemasonry.[28] In Scotland however, operative lodges, which soon after their introduction admitted gentlemen and introduced freemasonic rituals and customs, maintained their status of building trade organisation.[29]

Nicholson's father, George, his uncle Donald and his brother Hepburn Nicholson, were all members of an operative stone-masons lodge in Haddington.[30] Peter seems never to have joined this lodge, but instead went to London in the last decade of the 18th century. Nicholson became very interested in geometry and its applications to architecture, where he strove to develop an efficient system of graphical communication for the use of architects and craftsmen. He seems to have brought with him the knowledge of the techniques related to stone-cutting which he learnt in Scotland, and soon after his arrival to London started a drawing studio for craftsmen in Berwick Street, Soho. This served as an institute for mechanics and workmen who were facing an open, post-lodge market, but where, for the same reason, the instruction was lacking. His knowledge of projection techniques used within the stone-masons craft and the carpenters trade proved to be unquestionably important in this context.

We can best trace the invention of Nicholson's system of projection through his own account of events:

> In 1794 I first attempted the Orthographical Projection of objects in any given position to the plane of projection; and, by means of a profile, succeeded in describing the iconography and elevation of a rectangular parallelpipedon: this was published in vol. ii of the *Principles of Architecture*.[31]

In the same work, Nicholson (1822) further explains that in 1796–7 he had met Mr Webster, a drawing clerk for Mr Mitchell in Newman Street, who pointed out to him the similarity of his work with that of works from France. In 1812 Nicholson was given Monge's treatise by Mr Wilson Lowry, famous

engraver, and subsequently had it translated by one Mr Aspin into English. Nicholson published the major points of the technique of Descriptive Geometry in his *Architectural Dictionary* of 1813.

His account of the practical need for geometrical education appearing in his 1839 edition of *Practical Treatise on the Art of Masonry and Stone-cutting* described what he believed was the most important aspect of the new language of graphical communication:

> To be able to direct the operations of Stone Masonry, taken in the full extent of the Art, requires the most profound mathematical researches, and a greater combination of scientific and practical knowledge, than all the other executive branches in the range of architectural science . . . To enable the Workman to construct the plans and elevations of the various forms of arches or vaults, as much of Descriptive Geometry and Projection is introduced, as will be found necessary to conduct him through the most difficult undertaking.[32]

To this end Peter Nicholson invented and used a system which he later called Parallel Oblique Projection, an orthographic system of projection which makes use of an oblique plane, so as to provide both the presentation of an object and the method by which such an object is to be executed at a building site. Nicholson's own system of orthographic projection undoubtedly rested on his knowledge and experience both of what was considered the necessary knowledge of builders' craft and of what was going on in this subject on the Continent. He published a full treatise on the system of Parallel Oblique Projection four years before his death, in 1840. Like most of the works in this genre, it was written for the engineer, architect, surveyor, builder, mechanic, and the like, suggesting that the technique should be used as a universal language of graphical communication among the different parties involved in building trade.

Nicholson's system can be explained with the following example (Figure 5). The plane which is labelled as αβ?is the inclined plane of projection. The two orthogonal planes of projection are vertical and horizontal, given by their intersecting line UV. The vertical and horizontal projection of an object serve as a basis upon which the inclined projection is constructed, thus giving both the measurements (in vertical and horizontal projection) and a pictorial presentation of the given object placed in the inclined plane αβ.

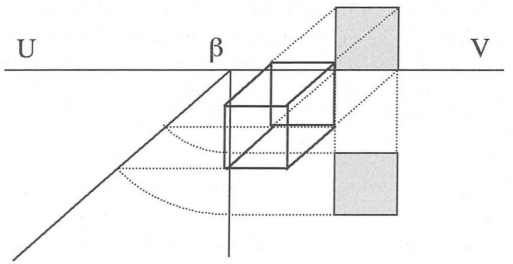


Figure 5
Diagram showing the principles of Nicholson's system

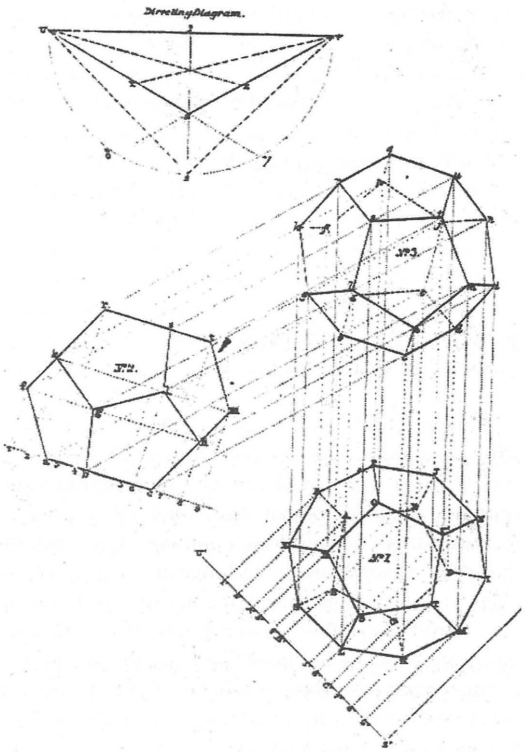


Figure 6
Plate 20 from Nicholson's *Parallel Oblique Projection*, published in 1840, showing the body in three views; the system also offers an easy method to obtain real measurements

Syllabi of the architectural and engineering schools in England in the period between 1840 and 1860 show that three techniques were taught under the title of Descriptive Geometry courses: Monge's Descriptive Geometry, Farish's system of Isometrical Perspective, and Nicholson's Parallel Oblique Projection system.[33] Farish's Isometrical Perspective came to be regarded as an answer to the difficulties posed by Descriptive Geometry, as it was regarded to be simple and visual in contrast to Descriptive Geometry which was given the label of an «abstract» technique. Its main shortcoming, however, was obvious, namely the presentation of an object purely in its pictorial form. The real measurements can not be taken easily from the diagram, nor can it offer a simple graphical method for extracting them.

Nicholson's invention of Parallel Oblique Projection stands somewhere between Descriptive Geometry and Isometrical Perspective: by the introduction of a third plane of projection inclined towards the first plane, two of the most important objectives of orthographic projection in communication are satisfied. Firstly, measurements are easily extracted from the drawing and the view of the object is less «abstract» —in other words, it gives a picture which delineates the main characteristics of the object in its entirety, not in various planes. Secondly, Nicholson's system offers an optional possibility of introducing more inclined auxiliary plans which enable the user to transfer objects freely to positions that are most appropriate for certain purposes.

However, Nicholson's system had another feature which added value to its applicability in the syllables of the architectural and engineering schools of England at the time. As already mentioned, Nicholson drew upon his experience of the stone-masons' craft and based his technique on what was at the time accepted language of graphical communication among the Scottish craftsmen. When he came to England however, he also joined the speculative Masonic brethren: as both an author and a practitioner, he worked as a superintendent of the building of the new court-houses at Carlisle, between 1805 and 1810, for Robert Smirke, architect of the British Museum. Both men were Freemasons, and Nicholson first met Smirke through Freemasonry as both were members of the Old Cumberland Lodge, London.

The influence Freemasonry had played on the establishment of the architectural profession is primarily in the role of Freemasonry during the process of the establishment of the colleges of the University of London and their subsequent development of the architectural education. There existed an underlying network of leading architects, both practitioners and educators, who belonged to the small number of London lodges. A particularly interesting example offers history of the Jerusalem No. 197, which met (and still does) in London. Members of this lodge included the architect of the new Houses of Parliament, Sir Charles Barry (1795–1860),[34] Lord Reginald Brougham (1778–1868)[35] one of the founders of the University College London, Charles Hutton Gregory, President of the Institution of Civil Engineers in 1877, Horace Jones (1819–1887) President of the Royal Institute of British Architects, Thomas Hayter-Lewis (?-1889), the second chair of architecture at UCL and the Vice President of the Royal Institute of British Architects, and John Loughborough (1817–1897) architect to Lincoln Cathedral. But other architectural educationalists were also part of the fraternity: Banister Fletcher (1866–1953) who worked extensively on establishing architectural history as a subject at King's College and was the first to publish a work on the subject —*A history of architecture on the comparative method in 1896*— was also an avid Freemason.[36]

There existed at the time, an underlying network of architectural practitioners which meant a subscription to the range of beliefs and mythology promoted by its establishment, effectively colouring the view of architecture as mirror of the divine order. The social infrastructure of the architectural profession in England, in the 19th century, was developed on the principles of brotherhood, rather than as an inclusive profession.[37]

Nicholson, although never rising to the higher echelons of the architectural profession, nevertheless associated with it through his Masonic connection. It may be that his background relating to the «original» and «operative» stone-cutting lodge gave also certain appeal to his technique in the professional circles. The system which he developed and subsequently gained the name of «British system of projection»[38] became widely used in the schools of architecture and engineering that were established in London in the 1840s.

Further developments in England

The degree to which the principle of the educational issue as defined by Monge and represented by his Descriptive Geometry were accepted in England (i.e. that it is a technique which develops intellectual powers by means of easier visualisation of space),[39] was best explained by two people. One of them was Robert Leslie Ellis (1817–1859), founder and editor of *The Cambridge Mathematical Journal,* who in his report to the Royal Commission of 1852[40] into mathematical education in England testified that:

> the method of which it [descriptive geometry] makes so much use, namely, the generation and transformation of figures by ideal motion, is more natural and philosophical than the (so to speak) rigid geometry to which **our** attention has been confined.

A further clear description of the difference between Continental and English spatial awareness was given by Olaus Henrici, a Dane, who in 1870 succeeded Thomas Archer Hirst (a Continentally trained mathematician) in the Chair of Pure Mathematics at University College London. He introduced a course in «Modern Geometry and Graphical Statics», which he described as follows in the 1876–77 College Calendar:

> Students attending this class are . . . strongly recommended to join the Class of Geometrical Drawing which will be conducted throughout in connection with it (i.e. the course in Modern Geometry and Graphical Statics).

Henrici's views coincided closely with the educational concept and aims of descriptive geometry, and his approach to the subject was a consequence of his training in the subject to which his drawings, now lodged in the archive of the Imperial College, London testify.

During the period from the publication of Monge's treatise on Descriptive Geometry in 1795 to the early 1860's, a number of techniques which competed with Descriptive Geometry were published both in Britain and in France.[41] Of those only Farish's and Nicholson's techniques survived and have been used in architectural education.

By the time the English architectural schools started their work in the early 1840s, a mixture of various techniques were used for teaching and communicating architecture. It mixture was often called Descriptive Geometry, but little of the real principles of that subject were actually taught to the students. What was taught was a system of projection invented and put into print for the first time by Peter Nicholson.

In the 1840, with the first publication of his full-length treatise on his technique, Nicholson's system of projection became so widely adopted that reference to its inventor disappeared in the manuals and syllabuses. The syllabi in descriptive geometry changed very little in this first phase of establishing the architectural profession and its institutions, during the first twenty years of the architectural schools in England, from 1840s to 1860, after which descriptive geometry ceased to be taught as a subject to architects altogether, and «graphical geometry» was taught along side perspective drawing, which has remained to be the case up to present time.

The two main schools of architecture, which were mentioned earlier, adopted a different approach to architecture in general, and consequently, geometry was regarded, in case of University College London, as a tool for exploring the possibilities of design and gaining a richer vocabulary, while at King's College, geometry's role was primarily that of communication between the craftsmen, architect and engineer. Thus, while University College London gave more time to students to explore geometrical systems in order to develop their own architectural vocabulary, it did not give comprehensive instruction into the actual systems of graphical communication already existing. King's College on the other hand, did not encourage invention of one's own architectural vocabulary, but because the communication between architects, engineers and craftsmen was considered as the most important part of architectural student's education, the education in geometry and graphical communication was of a high standard.

To conclude, Descriptive Geometry did not survive, in its original form, the initial translation into the English language in the first half of the 19th century. The reasons for this were political (wars between France and England at the time), philosophical (different preconceptions in treating and teaching space in these two cultures), and sociological (Nicholson's technique had the backing of the professional establishment through his

Masonic association with the highest echelons of the architectural and engineering professions). During the first half of the 19th century, between the initiation of its study in France and the British interpretation and further developments of Descriptive Geometry, it is clear that in Britain, graphical geometry, (geometrical drawing and descriptive geometry in combination) was accepted as a method for solving practical problems in architecture and engineering, with a mystical connotations attached to the it through the connection with the stone-cutting. It, however, gained little validity (apart from the sole example of Henrici, earlier mentioned) in terms of its applicability to mathematics. In France however, Monge's work was linked to that of his pupil Jean Victor Poncelet (1788–1867), if not in a clear line of succession, than certainly as a kind of inspiration to the invention of Projective Geometry in 1822. That apart, descriptive geometry (or its variant) in England ceased to be part of the syllabi of architectural and engineering schools as early as 1860s; and was replaced by the subjects related to architectural drawing and model-making, while it remains to be a subject of study in most continental European schools of architecture and engineering.

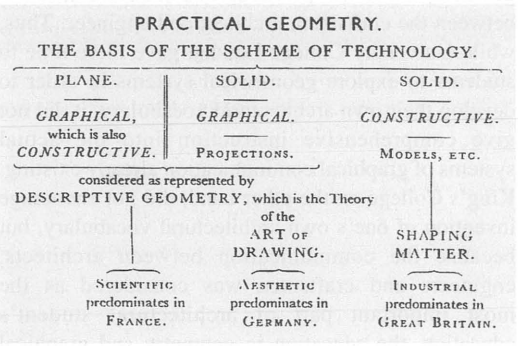


Figure 7
Plate from Cunningham's *Notes on the History, Methods and Technological Importance of Descriptive Geometry* (1868) comparing the systems of graphical communication in France, Germany and Great Britain. The author described history of Descriptive Geometry in England and the teaching practices of the subject in Germany and France. This diagram refers to Cunningham's argument that not only were these teaching practices different in the three countries, but that this was a consequence of the general differing predispositions in the way that space is perceived and taught

Notes

1. See Booker (1963).
2. With the changes on the continent, mostly initiated by the French revolution from 1789, the need for university level institutions offering education in practical subjects such as mining, engineering, medicine and architecture, became more acutely felt. The change, when it came, was influenced by the ideals of Enlightenment and advance of both institutions and prominent individuals who promoted a view that practical education is no less worthy than theology and moral philosophy. The sharpest criticism of the old English Universities at the end of the 18th century came from the north —the scholars in the universities of St. Andrews, Aberdeen, Glasgow and Edinburgh (University of St. Andrews was founded in 1411, making it the oldest Scottish university; Glasgow was founded in 1451 by a bull of Pople Nicholas V; Aberdeedn was founded in 1495, and finally the University of Edinburgh in 1583 under Presbyterian auspices of the Edinburgh City Council), who claimed a superiority in educational approach, by spreading and promoting the philosophy of Enlightenment. See Hoppus (1837, 12–33).
3. See Wolf (1935, 451–2).
4. See Taton (1951), also Sakarovitch (1989, 1995).
5. All of which were related in some way to stone-cutting. These techniques employed systems which Monge later incorporated within the system of descriptive geometry.

The main works were those of:

JOUSSE —Secrets de l'Arcitecture 1642
BOSSE —La practique des trait pour la Coupe des Pierres 1643
DERAND —L'Architecture des Voutes 1643
DE LA RUE —Traite de la Coupe des Pierres 1728
FREZIER —Traite de la Stereotomie 1738.

6. See Sakarovitch (1989) for full explanation of Monge's solution to the given task.
7. First translated in 1809, as already mentioned, while England was engaged in the war with France on and off during the period 1792–1815.
8. Claude Crozet (1790–1864) published *A Treatise on Descriptive Geometry for the use of the Cadets of the United States Military Academy*, New York, 1821. Crozet was born in Villefranche, France and was educated at École Polytechnique. In 1807 he was commissioned in the artillery. During the retreat of Napoleon's army from Moscow, he was captured and remained a prisoner in Russia for two years, being released only after the fall of Napoleon. Crozet then resigned his captaincy, but rejoined the army on the Emperor's return from Elba. After he left the army in 1816 he determined to seek his fortune in a new country. General Simon Bernard, a distinguished

military engineer, had just been appointed to a position in the engineering services of the United States army, and Crozet accompanied him to America. On the recommendation of Lafayette and Albert Gallatin, Crozet was appointed on 1st of October 1816, the assistant professor of engineering at West Point Academy and on 6th of March 1817 professor and head of the department.

9. In France as previously listed; in England work of Moxon —Mechanick Exercises; or the Doctrine of Handy Works-London, 1677–93–1700.
10. Booker (1963, 89).
11. Although England produced the first official Grand Lodge in the World, there have been numerous attempts by freemasons worldwide to regard this as only one of the many established at the time, and only the one which was officially and publicly known as the first Grand Lodge. No conclusive evidence points to this however. In more recent times, there have been academic attempts to prove the same point —namely see Stevenson (1988).
12. See Worsnop (1993).
13. The Masons' Company of London was a trade organisation and existed by prescription, its trade being regulated by the Court of Aldermen of which there are records as early as 1356. See also Colvin (1978, 18).
14. An exhaustive list of literature has been produced on the subject by the members of the Quatuor Coronati Lodge no. 2076 in London since its establishment in 1886 to the present day.
15. Entry to the building trade was guaranteed for the sons of its members only, and everyone else had to satisfy a number of prerequisites in order to join and subsequently to be allowed to practice the trade freely. Those who wanted to become masons had to serve an apprenticeship of seven years, after which they worked as «journeymen» for several years. The term «journeyman» is a corruption of the French journeé —the logical conclusion being that journeyman masons were those who worked for a day's pay. Journeyman masons could then apply to the Company of Masons to become master masons upon the examination and a payment of fees.
16. See Conder (1894), also London, Court of Common Council (1694).
17. See Knoop (1935).
18. The first Constitutions of Freemasonry were written by Rev. James Anderson (1680–1739), who was a Scottish Presbyterian educated at the University of Aberdeen. He was commissioned by the Grand Lodge to provide a history of the Fraternity. During the process, the majority of the records of the four constituting lodges which founded the Grand Lodge disappeared, an occurrence which has been the subject of considerable speculation. Ever since this convenient disappearance of original sources, a myth was created within the rank of Masonic historians that Anderson had access to the original documents and archives which lead to the real roots of Freemasonry, but an entirely fictitious history was manufactured by him to capture the imagination of its members. See Hamil (1986).
19. Christopher Wren, who is often referred to as the greatest English architect of his time, was a mathematician and an architect, founder and first president of the Royal Society (1660–1682). He built St. Paul's Cathedral after the Great Fire of 1666.
20. Colvin (1978, 22) quoting from an unpublished paper by Sir John Summerson in his possession, on the architecture of the London Temple.
21. See Castells (1917).
22. See Hall (1841, ix) and Heather (1851, i-vi).
23. William Cunningham (1849–1919) was economist and churchman and is largely credited for establishing economic history as a scholarly discipline in British universities. Cunningham taught from 1891 to 1897 as professor of economics at King's College, London. His most important and complete work is *The Growth of English Industry and Commerce* (1882).
24. Cunningham (1868, 25). Of the earlier mentioned treatises on stone-cutting, Frezier's work was the first to employ the horizontal and the vertical projections for the definition of voussoirs; descriptive geometry later adopted the system of two projections without necessarily employing terms or concepts of what was horizontal and/or vertical. In this respect, the novelty of descriptive geometry was to represent and take the user through the method of generating objects by movement and intersection of plans and not to represent them as they would appear in relation to built objects (i.e. vertical and horizontal).
25. The word was first used in English language by Cunningham in 1886.
26. See Grattan-Guinness and Andersen (1994).
27. See Lyon (1900).
28. See Knoop (1935).
29. Lyon (1900, 37).
30. Records from the Grand Lodge of Scotland note that Haddington Lodge joined the Grand Lodge by Chapter of Confirmation dated 30th November 1753. Haddington Lodge informed Grand Lodge of Scotland of the members which were already present for the first time in 1753, and then every year about new members. The records for 1754 show that most, if not all, of the people who joined were masons by trade. Not all of the yearly records show the profession of the candidate, it changes from year to year. On 14th August 1770, Donald Nicolson was recorded as being admitted to the lodge in the previous year. George Nicolson in the record for 15th November 1756, was listed as a member of Haddington

Lodge. In the record for 1779 and subsequent ones until 1805, Hepburn Nicolson was mentioned, first as admitted to the lodge, and later as an officer to the lodge.

31. Nicholson (1822, 46–7).
32. Nicholson (1839, 47).
33. Calendars from King's College London and the University College London as listed in the reference list.
34. Sir Charles Barry was father of the architect Charles Barry (1823–1900), who in 1877 became president of the Royal Institute of British Architects, and grandfather of the architect Charles Edward Barry (1855–1937). All three were Freemasons, members of the Jerusalem Lodge No. 197.
35. Henry Peter Brougham, First Baron, was a lawyer, British Whig Party politician, and Lord Chancellor of England (1830–34). Educated at the University of Edinburgh, sponsored the Public Education Bill of 1820; made antislavery speeches and advocated parliamentary reform. During the 1820s he helped to found not only the University of London but also the Society for the Diffusion of Useful Knowledge, intended to make good books available at low prices to the working class.
36. The development of architectural history in England as a subject to be taught at the newly established architectural schools was a continuation of the practice established since the late 17th century, in which clergymen, squires, lawyers and doctors were absorbed in historical contemplation, a practice which Watkin (1980, 49) describes as one in which studies and descriptions of the architectural past were undertaken in a spirit of nationalism and religious enthusiasm. This field of study by non-architects was developed between 1660 and 1730 (Watkin 1980, 34); and it was only with the founding of the architectural schools that the subject became a matter of study by professional architects. Banister Fletcher was the first to write a comprehensive guide to the subject, dedicated to students of architecture. His book followed the development of architecture from the ancient times to the 19th century. It has been reprinted in numerous editions and is still in use by students of architecture today.
37. For the description of fraternal culture related to the 19th century history of science in England, see Gay and Gay (1997).
38. Grattan-Guinness and Andersen (1994).
39. Monge wrote on this educational aim of descriptive geometry in following words:
«The second object of descriptive geometry (first being to represent, with exactness, in two dimensions, three dimensional objects) is to deduce from the exact description of bodies all which necessarily follows from their forms and respective positions. In this sense it is a means of investigating truth; it perpetually offers examples of passing from the known to the unknown; and since it is always applied to objects with the most elementary shapes, it is necessary to introduce it into the plan of national education». Monge (1811, 2).
40. Great Britain, Parliamentary Papers (1852–53, 224).
41. Farish (1820), Cousinery (1828), Nicholson (1840), Hardman (1853).

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Stone buildings in Salento (Puglia, Italy): Materials and techniques

F. Leccisi

Apulia and in particular Salento area underwent a deep transformation which changed the native look and gave rise to a balanced relation between the landscape and the habitat. Nowadays this balance is in crisis because of split up factors, brought about by the new economic forces, which begot deep changes in agricultural structure of the South of Italy and led up to the breakdown of the middle farm, cornerstone of the traditional agriculture. The subdivision of the agricultural lands has engendered their abandonment or their conversion into lots. The *trullo*, house with conical roof, typical apulia construction, becomes a villa for the week-ends, loosing, then, its environmental feature and, as a consequence, the countryside is no more an economic resource to those who work in it, but a «landscape» to be admired. Ancient centres, often forsaken because of the bad sanitary conditions, became object of consumption to be painted and illuminated in order to draw visitors' attention and to sell, at a higher price, the *trulli*, the farms and the houses placed in that area.

The farms

In Apulia the farms, both for the territory conformation and for the consequences of the economic development, have a particular feature and represent the most rational and modern form of working organization and of conveyance surrender assignment of middle and big landed property. The farms consist of an agglomerate of cottages and of facilities necessary to give hospitality to a certain number of families, of head ovine cattle and to give the opportunity of manufacturing the milk to obtain its by-products. Another important characteristic of the farms is their inclination to the self-sufficiency, because they get by the land the necessary foodstuffs for a year and even provisions for the sowing. The origins of these agglomerates are very old: the great number of ruins, dated back to the Roman times, certify it. The farms, born as independent communities, as a consequence of the destruction of the cities and the towns, were given to gallant warriors or courtiers; then they were given to the feudatories, who used them as summer houses. The building complex consists of a central section on the first floor, where there are spacious rooms with a hall, intended for the owner. The cheese storehouses, and the warehouses for corn, oil and wine were annexed to the building (Calderazzi 1989). Along the sides of the courtyard, there are the staff lodgings, modest little houses often made up of just one room. The cattle has its place in the courtyards and in the stalls. The little church, the mill, the crusher and the facilities make the settlement self-sufficient. Some farms were built with a defensive shape; the farms placed in Otranto, on the Adriatic Sea, from where the Saracens' incursions came, are an example (Mongiello 1984). The peasants, converging on the

farms, felt themselves guaranteed for protection and survival; therefore they started to build their houses next to the farms, turning these agglomerates into hamlets, villages and towns. There are many exampla of these developing processes in Salento. Until the fifties, we have had three kinds of farms: the farm consisting of olive groves; the farm consisting of bare lands (prevalently used for grazing) and the farm consisting of olive groves and bare lands. Subsequently, and above all during the last twenty years, the land outline has been divided into four kinds: sheep farm, graniferous farm, olive farm and farm consisting of a complex structure. The farm *Carestia* (Famine) in Ostuni is the most representative farm with a complex structure. Notwithstanding its unauspicious name, it is a farm that gives rise to an agricultural and breeding centre (Mongiello 1996). The architectonical shapes of the construction are sumptuous and dated back to the beginning of the eighteenth century. It was built according to the archdeacon Massari's will, who was of Lombardic origin. The farm *Carestia* has come back to life thanks to the present owner's dynamism after a period of neglect. Nowadays, very busy agricultural and zootechnical activities take place in this farm.

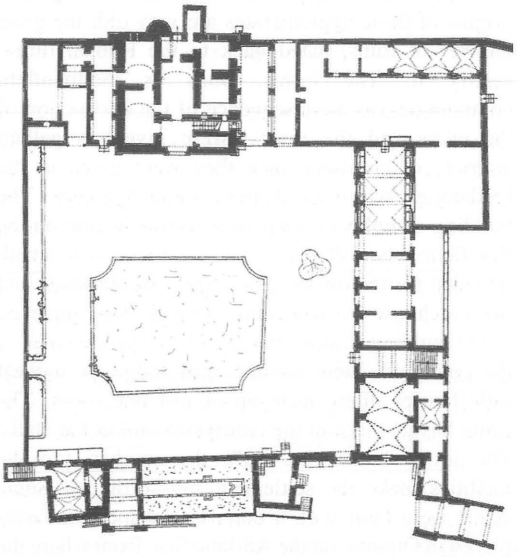


Figure 1
Planimetry of the farm Carestia in Ostuni countryside

It is to point out the plan of the fortified farms which have generally the shape of towers with a square or rectangular base, and are surrounded by stone pits and slits, having, at their base, a moat and a drawbridge. These fortified farms are representative of a moment of growth of a further step compared with the ancient hamlets, and testify some aspects of the Byzantine organization. The typical plan consists of the tower-shaped structures. The residence of the farmer is at the upper floors, while, at the ground floor, there are rooms to protect against the cattle, domestic habitations for farmhands and tenant farmers, and rooms and premises used as folds (Costantini and Novembre 1984).

The houses with corridor

The shape of town habitation is different. It has, almost always, a double room form; the fireplace is placed on the end wall and the rooms are built depthward, shaping the plan of the so-called house with corridor, *curreduru*. This kind of house consists of three rooms: the front and spacious one, known as *camera de nanti* or *casa de nanzi* (first room), and the other two, leaned against the end wall of the first room, with a common side, but not for this reason directly communicating. The corridor, *curreduru* or *carretturu*, is made out of one of the two smaller rooms to which is usually annexed the kitchen (Favia 1947; Simoncini 1960; Spano 1967; Colamonico 1970). The corridor, close to the inner division, is, on its upper part, bounded by a floorboard, called *ntaulatu*.

In the characteristic houses of Salento, and particularly in Taranto and Brindisi areas, it can be found a single room plan placed upon a basement, or a big room completely subdivided into four parts by vertical and horizontal separators: kitchen, alcove, little room and storehouse (Cazzato and Costantini 1996). The bigger houses consist, instead, of rooms placed one after the other. These corridor-houses consist of three rooms: a front and spacious one used as living room and other two with a common side, but not directly communicating. The upper spaces consist of two or three bedrooms, placed on the front line of the house or on the two rooms adjoining the corridor. An inside wall staircase allows the entrance to these rooms, while the staircase on the courtyard is used to

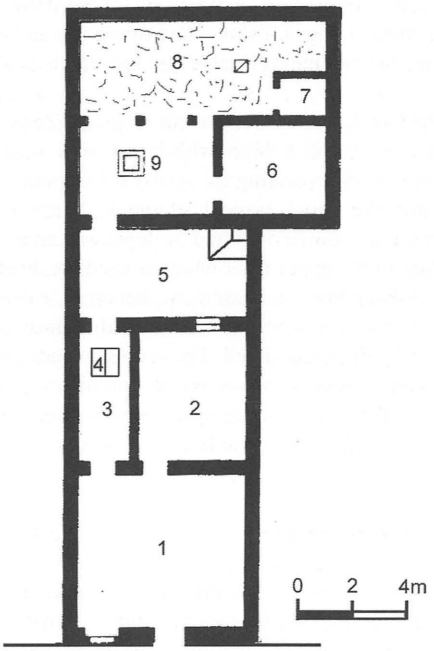


Figure 2
Plan of the house with corridor: 1) living room; 2) room; 3) corridor; 4) trapdoor leading to the cellar; 5) kitchen; 6) stall; 7) toilet; 8) vegetable garden; 9) cistern.

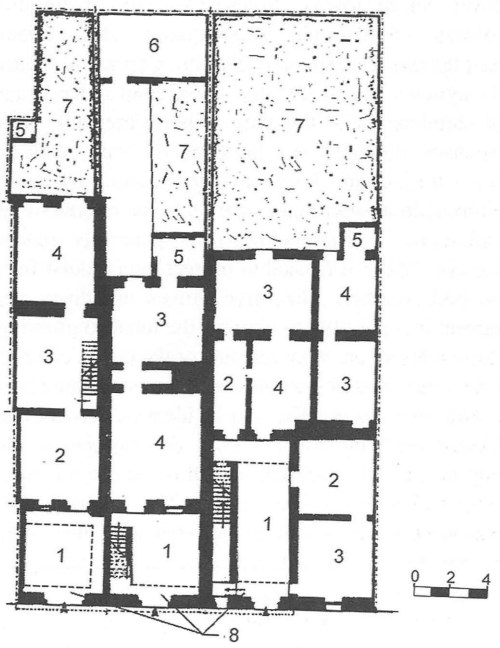


Figure 3
Planimetry-type of a house with court: 1) court; 2) entrance; 3) bedroom; 4) kitchen; 5) toilet; 6) stall; 7) vegetable garden; 8) *mignano*

go up to the terrace.The corridor-house of Salento's area of Albania is enriched with the wine cellar, called *ciddharu*. It is noteworthy the wide diffusion of the use of the *curreduru* in Brindisi hinterland, in the Murge of Taranto, the first terraces of the continental upland and the median narrow of the peninsula. In Lecce's tableland, the house *a curreduru* lacks the cellar and has only one storehouse whose entrance is on the corridor.

The houses with court

In Lecce area the kind of construction with the corridor-shaped entrance is replaced by other kinds of construction. The Lecce's peninsular territory is made up of houses which do not directly overlook the lanes of the suburb since they are substituted by the court, in common to more than one house. A courtyard of various shape and size separates the houses from the lane, as it happens in many places of the Mediterranean area: it is important to remind the Iberian *mesetas*, the Sardinian *campidani*, the coastal plains and the steppes of the Balkan peninsula. The new element is the staircase leading to the covering upper porch, used to expose agricultural products to the sunlight. The terrace also overlooks the public way (Costantini 1979).

The rural house usually consists of one or two facilities, almost always at the ground floor, placed in a group of one room houses inside a courtyard of collective use. These houses are placed on straight fronts, converging at right angle, and they do not always take the four sides of the courtyard up. As a matter of fact, there are simple or right angles formations of houses, while, on long and narrow courtyards, two groups of houses side by side to the road are often placed.

It is necessary to pay attention also to the house settlement of the Salento's area of Greece, made up of

eleven small towns: Soleto, Martano, Calimera, Zollino, Sterniatia, Castrignano dei Greci, Melpignano, Corigliano d'Otranto, Caprarica, Castri, Martignano. The soil is dry, the ground is Karst and the landscape is desolate. There are not wide expanses, the fields are bounded by walls made of stone, ashlars and bricks and built, stone by stone, without binder (Costantini 1988). In the middle of the settlement, a *trullo chipuro* is generally placed (Leccisi 1994); it is used to protect the colonist from the bad weather. The olive graves are dusty and rugose; it is possible to observe the tobacco growing. These villages are what remains of the Greek colonies or of the Byzantine colonies or of the once dated back to Ottoman exiles. The nearly identity between the ancient Hellenic houses (their descriptions in the Odyssey are an example) and those of the Salento's area of Greece is of no wonder. The architecture of the Greek house is simple: the courtyard, surrounded by porches, opens on the road or on an open space. Under the porch there are premises for the stables, the mills, the lodgings for slaves and foreigners and in the centre, behind the vegetable garden, there is Zeus' altar.

The Greek house of the Salento replaces Zeus' altar with a well and a high whitewash wall with two folding doors separating the courtyard from the road. Among the most typical elements there is the staircase laid down on round or depressed arches and leading to the upper floor which is used for dwelling. The ground floor, or basement, becomes a cellar, a lumber-room, a woodshed, or it is the place where less well-off people dwell. The staircase leads even to a balcony, called *mignano*, which dominates the main door of the court, setting up a «zip» between public life (the road) and private life (the court).

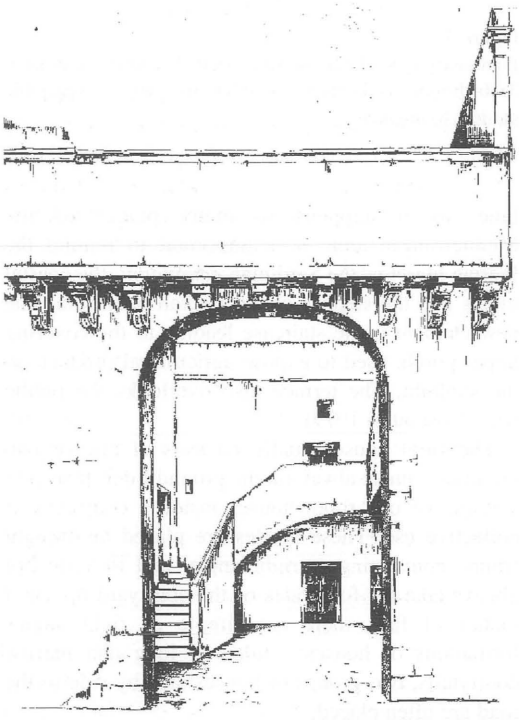


Figure 4
Mignano

Building techniques

The architecture of Salento uses poor materials and simple building techniques and this reveals a deep knowledge of the characteristics of the materials and of the constructive rules by skilled workers. In Salento's small town centres, we can find master masons, able to build particular masonry vaults (vault with *spigoli*, vault with squarig and vault *gavetta*) or openings in the walls (Leccisi 1991, b) with a technique improved during the centuries, without the use of centreings but only using local materials such as the tuff, the *carparo* and the *leccisu*. The Lecce's stone is, indeed, the basic element which influenced the whole architecture in Salento in such way that it is possible to affirm that the Lecce's baroque owes its extraordinary flourishing to the abundance of this stone, easy to work and to carve (De Marco and Bolognini 1995). The bigger quarrying centres of this stone are in Lecce, Cursi and Melpignano. There are several studies on the three kinds of *leccisu* usually used (Stella and Marrone 1993). The types extracted from the working quarries of Cursi and Melpignano are less studied. We shall briefly list them: *mazzara* (3–4 m thick); *piromafo* (1,34 m); *cucuzzara* (1,90 m); *bianca* (0,50m); *dura* (5,40 m); *dolce* (5,40 m); *saponara* (0,30); *gagginara* (0,60 m) (Arditi 1888, 1894; De Giorgi 1902). The whole works are at open sky, *a fossa*, and go to a depth of 30 meters, whence the name *tagghiata* to the place where the quarry is situated. The kinds of tuff,

generally quarried, are the white tuff and the yellow tuff. During the quarry we will go on removing the *cappellaccio* (friable and concretionary calcarenitis), then it is prepared a quarry plane, deepened by going on extracting. The rock was dug out by using a pick with a long handle and with the double iron arms of different lengths, named *zueccu*. As every work, even the extractive one shows positive and negative consequences. It represents, indeed, an irreplaceable profit-bearing commitment for same sectors of the commerce and the industry in Apulia, but it deteriorates the environment. In Salento, an extractive activity on mountainous or hilly slopes, disfiguring the landscape, is not yet developed. This happens according to the morphology of the area, dominated by Karst plateaus. The intensive exploitation of the layers using the technique *a fossa* tends to transfer research areas, causing the problem of the excavation filling up and of the use of the debris. The quarries filled up with debris are precarious and unstable; the embankments built, at the present time, using debris are exposed to hidden dangers. Therefore we firmly hope that the extractive works will be carried out paying attention not only to the quality, to the availability of the materials and to the proper means for their rational use, but even putting into practise new standards looking after both economic interest and the public welfare.

Tools and masons

It will be simple to understand that during ages in which the prefabricated element was unimaginable to use, the builder job, the *frabbrecatore*, was not an easy occupation because it required responsibilities and sacrifices. The mason living in that age had a wide tool-kit made by local forgers. A long picturesque list comes out by some ancient masons' memories: *lu martiedde*, *la cucchiara* (trowel for mortar), *lu cucchiarine* (to retouch), *lu squadre* (to shape stones and tuffs), *lu squadre fauze* (for the roughness after the setting), *la marteddina* (to reduce stones), *la marteddina grossa a ddiende* (to rough-hew uncut stones), *lu pecone* (to work the stone for inside places), *lu pecone a jascia* (an axe-shaped pick to rough-hew), *la mannara* (to square the tuffs), *la strufina* (jointer to smooth stones, particularly those of the front), *la strufina tonna* (to hollow out cornices and capitals), *lu rambotte* (to level the freestones), and different saws used for stones and tuffs, named *serracchje*. Then, hoes, wedding hoes, shovels, poles, *caldarine*, wooden and iron barrows, must be added. Therefore, it was used the *macèlana*, a monkey winch, substituted by modern skip hoist to rise mortar and lift it up. The proper stones and tuffs upright setting was checked by *lu piombo*; lines were drawn by using a thin line , *lu lenze*; to check the horizontal plane it was used *lu levèdde;* finally the mortar necessary to retouch plasters and walls was put on a sort of palette, *lu sparvière*. The most skilful masons were called *mèste*, i.e. masters, and the work managers were called chief masters, *cucchiara*: they were almost always the building planners. The contribution brought by stone-cutters to the buildings was of great value; to these artists we own the sculptures of the keystones of the internal and external capitals, and of the figures, the symbols, the coats of arms and every sort of embellishment.

Construction of foundation, walls and pillars

To lay the foundations, first of all it is necessary to remove the vegetable land to reach the stratum suitable to support the weight of the upper construction. Then the land is horizontally levelled by using the mattock and, after setting a stratum of mortar, *murtieri*, made up of lime and vegetable land, to level the setting surface, it is built the so-called *linea di punta,* on which the wall is erected. There are two kinds of walls: the first is a non-cavity wall usually built inside the constructions named wall of *purpitagnu*, 20–30 cm thick; the second is maximum 1,20 m in thickness and made up of two ashlar covers, squared only on three faces, 20–25 cm thick, the *curescie*, with an interspace filled with debris or with the *bolo*, a type of clay common in the zone. Sometimes particular ashlars, *ligatore*, were set in *opera di punta* at a distance equal to1,50 m, to link the two covers. Particular care was paid to the building of angle-irons, choosing the best stones, without defects, named *cantuni*. In the residential buildings which, in Salento, usually have two floors outside the ground, the main walls is 23–25 cm thick and the maximum room size is about 5m. The *linea di punta* in foundation is 60 cm in breadth.

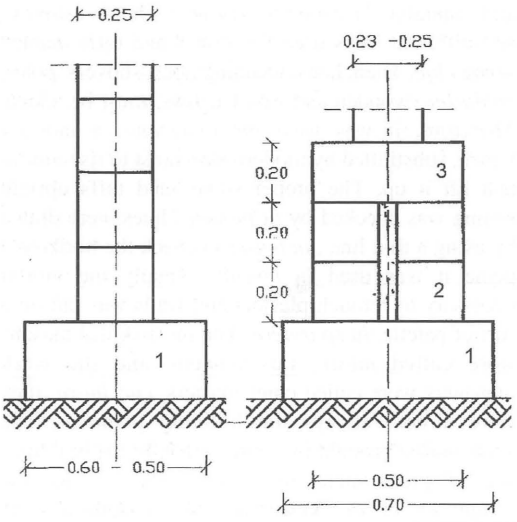


Figure 5
Fundations of the wall: 1) *linea di punta*; 2) *curesce*; 3) *ligatore*

In the buildings constructed for oil mills, for the first tobacco manufacture, for large stalls, the size of the vaults, unload on pillars connected with side walls and intermediate pillars. In this case the outside walls are 50–60 cm thick and the intermediate pillars have a cross section whose four arms have a middle size equal to 60 cm × 60 cm. The *linee di punta*, on which the outer walls of the building and the pillars are erected, are about 70 cm wide. A three workers team, made up of one mason master, *cucchiara*, one squarer, *mannara*, and two hodmen, set in a working day 5–6 mc of ashlars, equal to 20–24m^2 of walls.

Vaults

In previous researches (Colaianni 1967; Leccisi1989; Leccisi 1991a), the building techniques of the stellar vaults and of the vaults with square, typical of this territory, have already been studied. Constructive peculiarities are pointed out in this session.

Vaults with spigoli

For the construction of the vault with *spigoli*, also named star-shaped vault, it is not used the wooden structure: it is necessary the use of the *furma*, a wooden centring about 10 cm thick, circular arch shaped or three focuses shaped or elevated, fulfilled using planks 2,5 cm thick and 20–25 cm wide. The team is composed of 3 or 4 workers at least: one *cucchiara*, one *mannara* and one or two hodmen. Once erected the outer walls according to the aforesaid way, we will proceed with the building of the four corbels, *mpise*, and of the adjoining walls. The ashlars of the corbels are part of the wall it-self. After constructing the four *mpise* in the four corners of the room, usually costing of 4–5 lines of shaped stone, of which the last one named *summarieddu*, 20 cm thich, is very particular, we will go on erecting walls over the extrados of the next vault. The shape of the vault is drawn on each wall using a pencil; soon after it follows the phase known *as palumbredda*, i.e. the nick of the wall on the drawn line; this nick is 16 cm high and is variable from 0 to 5 cm in depth, starting from the top.

The *furma* is about 50–55 cm distant from the wall, so as the ashlars, which will form the groin 16cm high, are put both in the *palumbredda* and on the *furma*. After completing the first arch, the *furma* is moved to build the adjoining arch. Then, after completing the second arch, it will be linked together with the first arch by properly shaped ashlars, named

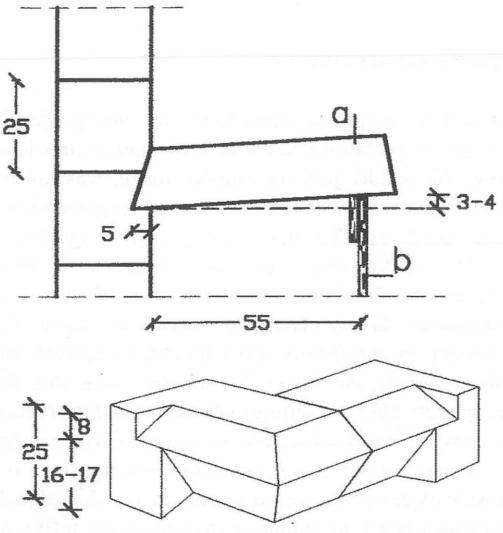


Figure 6
The *palumbredda* and the *summarieddu*

vele and *riga* 12 cm thick and with a maximum length equal to 110 cm. Over this measure, three ashlars are generally set. Therefore stones and scraps of different size, the *carica*, are placed on the arch; the biggest ones are placed at the ends, and the smallest ones are placed at the centre so to create a great contrast and a great compression among the ashlars. Near the *mpisa* particular ashlars, the *schiaffettoni*, pieces of l*eccisu*, wedge-shaped with a 45° angle, are set in order to fill the gap between the wall and the vault extrados. The construction of the third and fourth arch is similar to the previous one. Therefore we will go back to the first arch placing the *furma* at 50 cm and finishing the different groins. The central section is closed using tuff ashlars and soon after it is loaded up with tuff pieces in order to roughly level the vault extrados surface. Subsequently a stratum of *tufina*, i.e. the tailings of the tuff stone manufacture, is spread to make out the slopes; the next phase is the proofing. A squarer needs two working days to give shape to the ashlar used for the covering of a 5 m ¥ 5 m room, while a team made up of one mason master, one squarer and two hodmen needs only one working day to build the vault. The constructive phases of a star-shaped vault are shown in figure 7.

The length of the works depends on the patience and the accuracy of the squarer and of the mason master. To fix the price, the vault is generally valued about once and a half more than the room. The works are usually carried out in summer for two reason: firstly the mortar dries more quickly, secondly it is possible to avoid the undesiderable burdening of the masonry constructions caused by the rain.

The vaults with square, a squadro aperto

The vault with square is the most representative construction in Salento's art. There are two kinds of square: open and closed.

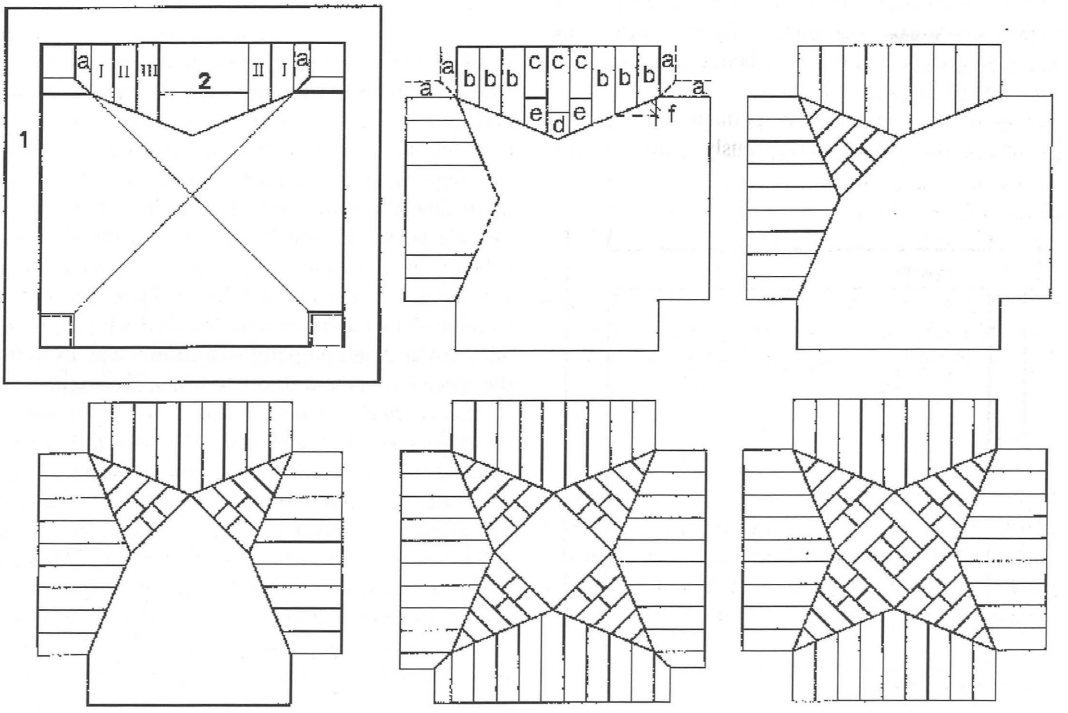


Figure 7
Constructive phases of the vault with *spigoli*

The vault with closed square, of which rare exempla exist, is supported by four brackets jutting out by the edge. The vault with open square is a mix among a cross vault, a basin-shaped vault and a keel-shaped vault, and it has, as horizontal projection, two triangles placed in the angular space of the room; the two contact lines between the vault and the pier, shape a right angle, i.e. with square. The vault has as horizontal projection a eight-points star, used to cover square or rectangular plan area with a proportion among the sides near at unity.

The constructive phase is more complex than that of the star-shaped vault, as the *mpise* of the star-shaped vault have one jutting cross edge, while the vault with open square has three edges: two jutting edges, in front of the ends of the square and one recessing, by the square vertex. The jut of the *mpise* from the walls is smaller than that of the star-shaped vault and reaches 40–50 cm, considering equal dimensions to be covered, yet with smaller section of angle piers, the vault has a greater rise and, as consequence, the room has greater volume compared with the star-shaped vault. The construction of the corbel, the *mpisa*, is shown in figure 9 where the ashlars are even numbered to better understand the constructing process.

The construction of the first of the four *mpise* starts by setting the ashlars —previously shaped by the squarer, marked with n°1 and called *prima manu*— which rest on the below wall for all their thickness, jutting about 2,5 cm. The *prima manu* ashlar is 25 cm high and the base of the front is usually 55 cm wide. The upper line of the *prima manu* juts 2,5 cm out more than the lower one. The ashlars made up of Lecce's stone, marked in the figure with n° 2 and called *cantune vacante*, rest on the *prima manu*; they are about 25 cm wide and 25 cm high. The ashlar forming the *cantune vacante*, marked with 2', is set after ashlar 2 and properly shaped in a way as to fill the space left in the wall by the ashlar. The upper line of the *cantune vacante* 2 and 2' is 5 cm jutting compared to the lower one. The ashlar 3, called *cantune vacante de tuzzatu*, rest on the 2 one, always respecting its external perimeter, but it leaned against the ashlars C, called *catene*, previously built and following the walls. The 3′ section can be extracted from the right-hand ashlar 3, while the 3″ section is properly shaped and placed at last. The upper line of these sections is 9 cm jutting compared to the lower one. The ashlars are always 25 cm high. The ashlar 4, called *nconigliatu di quarta manu*, is longer than the others, as, besides, following the external line of the ashlar 3, it is also fitted in the wall. The ashlar 4 is

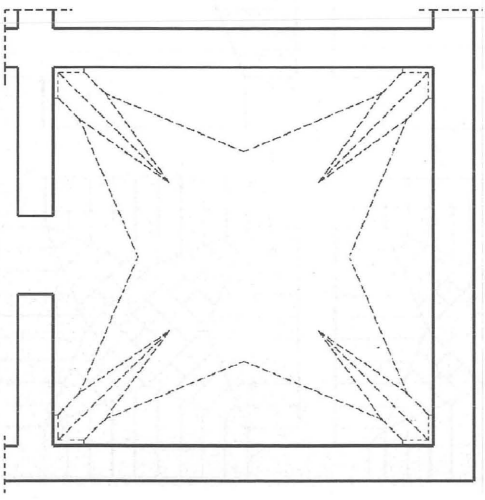


Figure 8
Vault with open square, *squadro aperto.*

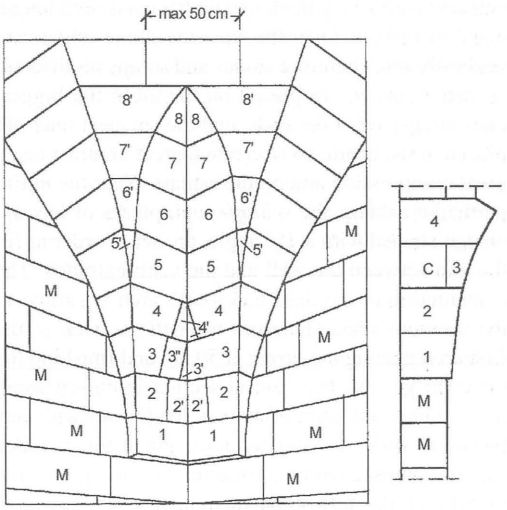


Figure 9
Constructive plan of the corbel, *mpisa*, of the vault *squadro aperto*

tapered, so that its height is reduced to 11cm and its line is 9 cm jutting compared to the lower one. After setting the ashlars 4 and 4′, both properly shaped during the works, the *mpisa* is completed. Therefore, after completing this phase, the construction of the other corbels and of the whole structure can be started, according to a constructive technique similar to the one used for the star-shaped vault, always observing the following phases: the construction of the first two *furmate*; the construction of the squaring by setting the ashlars 5 and 6, called *mesciu d'ascia*; the setting of the cap 7; the setting of the *vele* 5′ and 6′ and of the *righe*. The squarer needs two days to prepare the ashlars. A four workers team, composed of one *cucchiara*, one *mannara* and two hodmen, takes 3 or 4 working days to construct a vault of a room of a size equal to 5 m × 5 m.

Trough vaults and barrel vaults

It will be useful to examine the constructive techniques of the barrel vaults and of the trough vaults, locally called *gavetta* or *malrotta*.

The vault called *malrotta* is usually used for rectangular places and it consists of the crossing of two barrel vaults having the same radius of curvature. The constructive method is schematically the following. The wall is raised up to the line on which it should be placed the first ashlar, also called abutment of the vault. The abutments are built with ashlars made up of Lecce's stone, about 25 cm high, while the vault is built with tuff ashlars about 16 cm thick. At least four more masonry lines were built on the abutments, reaching one meter in height. Besides the wood centring it is prepared the *furma*, which is arch-shaped, of a selected curvature, little different from the one used for the star-shaped vault, as it is built with two identical arches, 20 cm far one from the other and linked together by wood pieces, the *mascelle*, on which 16 cm × 25 cm squaring shaped ashlars are placed up to 106 cm, while the first settled ashlars rest on the line of *leccisu* and have only one abutment. As concerns vault construction, it is necessary to start from the room centre, placing the *furma* in the middle perpendicularly to the long sides. The staggered tuff rest symmetrically on the *furma*: they create 20 cm jutting teeth, closing an arch on which is soon put the *carica* (load) consisting of shapeless stones. The *furma* is disassembled and moved of about 70–80 cm, so that it can be started the construction of a new arch, according to the phases previously described, with the tuff ashlars fitting in the ones of the arch previously built. Therefore the *carica* is set and the *furma* is disassembled. This process is repeated until the distance between the most jutting point of the last arch and the shorter wall of the room is equal to the half of the rope of the *furma*. The *furma* is rotated of 90° and placed with an end laying on the centre of the room wall and with the other laying on the prop built in a way as its keystone can adhere to the intrados of the centre line of the masonry arch previously built. The construction of the pavilion head will start by building a half arch, made up of ashlars progressively decreasing in length, resting on the abutment and on the keystone arch previously built.

The angles are closed by properly shaped ashlars, which are placed side by side along the bisector plane, so to finish the pavilion head. In figure 11 the constructive phases are schematically shown.

The barrel vault, round or depressed, is used to cover rectangular-shaped places. It is often used to cover corridors, small toilets, access areas or small and narrow rooms. Also the barrel vault is built with tuff ashlars, about 16 cm thick, which rest on abutments made up of Lecce's stones, 25 cm thick. The constructive process is similar to the one previously described but with some differences. The



Figure 10
Construction of sectroid in trough vault

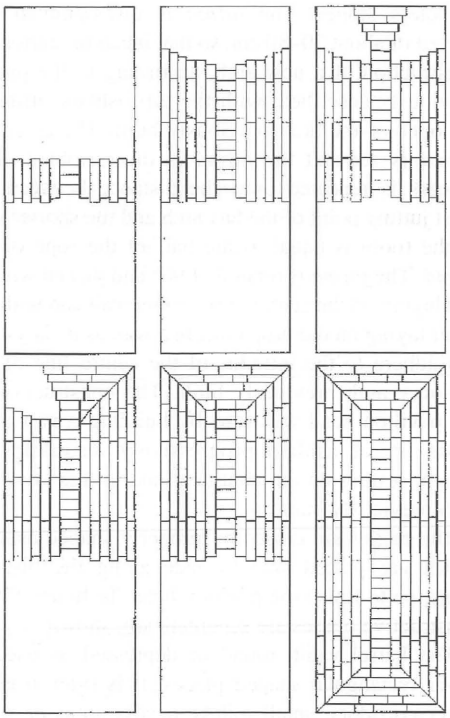


Figure 11
The constructive phases of a trough vault.

furma consists of only one wood arch; the vault intrados outline is drawn on the ending walls of the room. This is the phase of *palumbredda*, i.e. the wall is nicked from 0 to 5 cm in depth and for 20 cm in height. The *furma* is placed at a distance of 70 cm, side by side to one of the smaller sides. The tuff ashlars are symmetrically put and they rest on the *palumbredda* and on the *furma;* they close the arch and, once it is finished, they load it with shapeless stones. The *furma* is moved forwards for about 70 cm and the phases, previously described, are repeated till the whole area is covered. The last cap ashlars are properly shaped.

The stone pavements

The Lecce's stone, main element of the aforesaid constructive techniques with its other kind quarried in the basins of Cursi and Melpignano is used for



Figure 12
Construction of a floor paving

paving-stones, called *chianche*. Nowadays new building machineries able to produce simultaneously many paving-stones of the wanted thickness are used for the sawing, times ago carried out by hand. The traditional paving-stones were about 5 cm thick , 40 cm wide and maximum 70 cm long. The setting is very simple and it needs few rules to be observed. It is not advisable to set such a paving in presence of very low temperatures, because of the considerable degradation of the mortar used for the sealing of the joints. The paving-stones are set still dump in order to avoid the absorption of the water by the mortar and successfully setting. They are placed on a dry stratum of tuff dust, obtained in yard from the tailings of the squaring of the ashlars, and previously placed to measure the necessary inclines of the paving equal to 1%. After checking the solidity of the setting stratum and after removing any stones or impurities, the paving stone is placed, *ssettata*; then few light strokes, dealt by a non-metallic instrument, give the paving the right bond.

As concerns the sealing, the optimal distance among the dalles must be about 1,5 cm. The joints are sealed by filling their whole inner place with a fluid mortar consisting of water, sand and cement in which the water must have a sufficient quantity to give fluidity to the mixture and the sand and the cement must have a proportion variable from 2 to 1 and from 2,5 to 1. The mixture is poured in the joints by a flat instrument, one inch thick, called *mannara*

di chiamenti. Then the joints are finished using a little trowel and the overflown quantity is removed using a spatula or a round tool with a diameter larger than the one of the joint. A good paving depends, above all, on the care paid during these phases. A team consisting of four workers, one *cucchiara*, one mason and two hodmen, can set 40 m^2 of *chianche* in a day.

Stairs with monolithic steps

It is important to consider the peculiar construction of stairs with monolithic steps shaped with a particular technique.

The step setting is contemporaneous to the construction of the stairwell walls, so that the tuff ashlar, placed under and above the step, will be so high as to avoid the use of small ashlars, called the *mbasature*. As regards the flight stairs construction, it is necessary to put, at a distance of 1 m from the walls, a wood beam, called *chianetta,* sloping as the flight stairs and supported by props. One end of the steps, built with ashlars made up of Lecce's stone of Cursi of a size of about 130 cm × 26 cm × 40 cm, and suitably shaped, rests on the *chianetta*, while the other end rests in the wall for a length equal to 25 cm. The joints of the steps are filled with the mortar and the working team is usually composed of one hodman, one *cucchiara* and one skilful *mannara*.

Conclusions

We have briefly tried to explain the main phases of the masonry constructive technique in Salento. It is an art rather than a technique, which, nowadays, still lives thanks to the requisites of lastingness and easiness of the constructions and to their low cost. This art gives a singleness to the territory. Besides the knowledge of these techniques gives the opportunity of making properly restoring works which will preserve the heritage of the old town centres in Salento.

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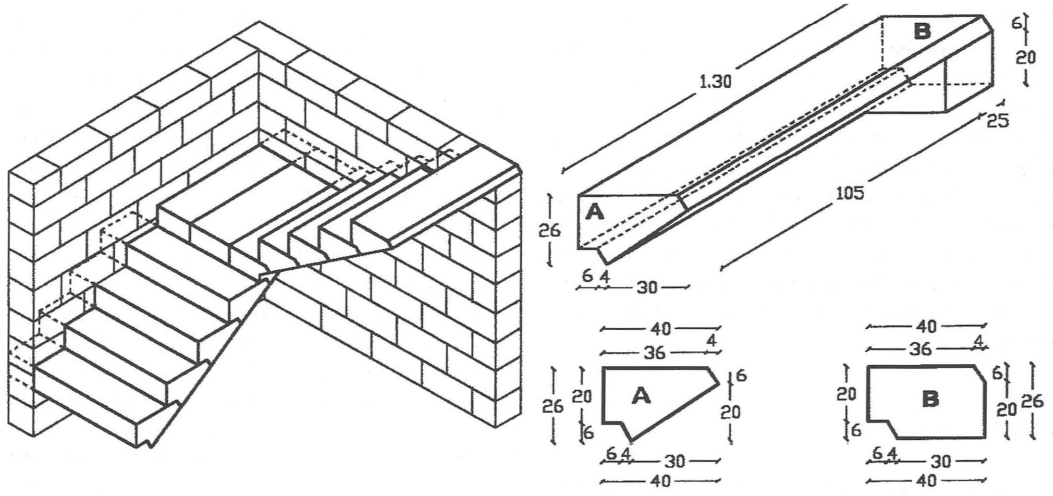


Figure 13
Stairs with monolithic steps: axonometric projection and particular step

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The italian archaeological heritage: a classification of types from the point of view. Of protection against earthquakes

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A classification of types of the Italian archaeological heritage is presented. The classification is centred on the structural behaviour and is the basis for subsequent studies on seismic vulnerability and risk. Twenty-two types are considered which comprehend the heritage of prehistoric, Etruscan, Greek and Roman Ages. For each type, there are given a description of the structural elements and a list of sites where specimens of the type are present.

Introduction

Recent Italian destructive earthquakes (Friuli 1976, Irpinia 1980 and Umbria-Marche 1997) had a heavy impact on the historical and monumental heritage. In particular, the archaeological heritage was recognized to exhibit a high degree of risk because of its state of decay.

In 1998 the Italian National Group for the Defence against Earthquakes started a research activity on archaeological heritage. The first phase of the activity was aimed at establishing a classification of types and studying the response of common elements under seismic actions. The vulnerability evaluation of the types and the design of restoration interventions, purposely conceived to respect the original conception of the works and their historical testimony, will be the subject of subsequent phases of the research.

The classification of types, centred on the structural behaviour, is presented in this study. Twenty-two types are considered which comprehend the heritage of prehistoric, Etruscan, Greek and Roman Ages. For each type, there are given a description of the structural elements and a list of sites —unavoidably non-exhaustive— where specimens of the type are present which are clearly recognizable, in the sense that they are not included in later buildings. The list does not include those sites where the presence of ancient constructions is documented by historical or literary sources only. Some types, like the Doric temple, are subdivided into sub-types depending on the different behaviour of the remains under earthquake.

Prehistoric age

Menhirs

Bari, Otranto, Giurdignano.

Menhirs are megaliths of lengthened shape made of a stone block, generally raw or irregularly hewn out, driven into the soil like a coarse obelisk, sometimes pierced. It is conjectured that menhirs precede dolmens. Menhirs may be of different shape (cylindrical, obelisk-like, prismatic, irregular) and their height is generally below 5 m.

Dolmens

Bisceglie, Giovinazzo, Corato, Melendugno, Minervino di Lecce, Mazzarino, Cava dei Servi

Dolmens are made of one or more horizontal plates supported by rocks driven vertically into the soil. The surface of the vertical rocks is raw or lightly hewn out, so that only point contacts are present between them and the horizontal plate. The basic type consists of four plates, three driven into the soil and the fourth for roofing, forming a square cella. More complex shapes are exhibited by some dolmens found in South-Eastern Sicily during recent archaeological campaigns; for instance, the dolmen found in Cava dei Servi (Ragusa) is made of big calcareous plates forming a cella with circular plan.

Megalithic walls

Regione molisana, Beneventano, Frosinone

The earlier type is the Cyclopean fabric, a continuous structure made of big rocks, with size 1 m or larger, raw or roughly hewn out, forming a dry wall.

The later type is the polygonal fabric (Fig. 1), made of blocks hewn out to form a polygonal shape, with the surfaces at the joints roughly smoothed, resulting in a facing consisting of an assembly of irregular polygons.

ETRUSCAN AGE

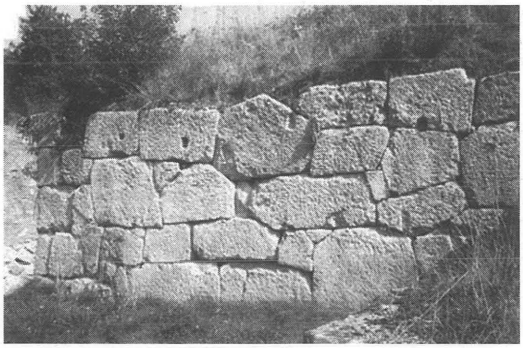


Figure 1
Wall in polygonal fabric, Alba Fucens

Etruscan town walls

Volterra, Roselle, Vetulonia, Fiesole, Chiusi, Arezzo, Tarquinia, Tuscania, Roma, Cerveteri, Veio, Vulci, Palestrina, Civita Castellana, Arpino

Etruscan walls and arch gates are always imposing: big blocks of calcareous rock, basalt or tuff assembled without interposition of mortar, to form a polygonal fabric or an *opus quadratum*. The stone is local and differs from zone to zone of Etruria: in Southern Tuscia —comprised between present Tuscany and the Tiber— the stone is always volcanic tuff cut in parallelepiped blocks with length 1.20 m and height 0.60 m, forming a two leaves wall filled by rough stones and mortar; in Volterra the walls are made of blocks in sandstone arranged according to the polygonal fabric or the *opus quasi quadratum*; in Roselle the walls consist of horizontal courses of irregular blocks 2–3 m long and 1–2 m high, and smaller stones filling the interstices; in Fiesole the walls are made of stones hewn out in a rough parallelepiped shape and arranged in horizontal courses with stones cut into wedges interposed between different blocks; in Arezzo the town walls are made of big green clay bricks.

Etruscan and Greek arch gates

Volterra, Perugia, Velia

The early Etruscan arch gates have a horizontal monolithic architrave, as those of the Mycenaean Age. The late gates have a round arch with three patroness godheads. The Etruscans built round arches since the 6th century B.C., as proved by the *Cloaca Maxima* in Rome which dates back to Tarquinius Priscus.

The unique example of arch in the Magna Graecia is the Porta Rosa in the town wall of Velia (the early Elea), made of two piers in sandstone supporting a round arch made of radial sandstone voussoirs, with a discharge arch above.

Corbelled vaults

Volterra, Quinto Fiorentino, Montefortini, Vetulonia, Tivoli

Corbelled vaults are found in monumental tombs, and consist of squared stone blocks projecting inwards closer and closer to each other until they meet.

Sometimes, a pillar supports the central block at the top (Fig. 2). The equilibrium of the corbelled vault is provided by the outer dry-stone wall which acts as a counterfort. The plan is often circular, but square and sometimes rectangular plans are present as well.

Corbelled vaults are only present in Northern Etruria. Often, they are covered by a soil tumulus which is enclosed by stones or a tambour.

Greek age

Town walls of the Hellenistic Age

Pompei, Velia, Paestum, Cefalù, Agrigento, Siracusa, Lentini, Megara Hyblaea, Tindari, Selinunte, Gela, Eraclea Minoa, Nasso, Erice

The walls of the Hellenistic Age result from the assembly of large blocks of sandstone, marble, tuff and sometimes green bricks, arranged to form dry walls according to the polygonal fabric or the *opus quadratum*.



Figure 2
Corbelled vault with central pillar

The *opus quadratum* consists of squared blocks. The fabrics are essentially three. The first fabric consists of a sequence of two or more blocks arranged in the longitudinal direction —the orthostats— alternated with a block arranged in the transverse direction —the diaton. The second fabric consists of a sequence of two or three courses of orthostats alternated with a course of orthostats of different size, lower and penetrating into the wall. The third fabric consists of all diatons, i.e. blocks arranged in the transverse direction.

The *opus quadratum*, broadly used by the Greeks in the classical age, was laborious because of the necessity to square, transport and position the blocks. In the Roman world, it was initially adopted to build the leaves for the *opus caementicium*, and subsequently abandoned.

The resistance of the wall is increased by cramps or dogs. Originally, dogs were simple swallow-tailed dowels in oak wood. Subsequently, cramps in bronze or iron were used with Z, I, C or double swallow-tailed shape.

The material is usually stone, but examples are present of green clay bricks as well.

Doric temples: basements

Caulonia, Imera, Agrigento

The colonnade of the Doric temple rests on a basement with three or more steps, the highest of which (stylobate) is the floor of the temple. The basements consists of courses of big parallelepiped blocks in local stone (sandstone, alluvial conglomerate, travertine, volcanic tuff), usually porous and cracked.

Doric temples: free standing columns

Capo Colonna, Agrigento, Selinunte

The Doric column is made of local stone, has no plinth and rests directly on the stylobate. The shaft, channelled during the finishing, is monolithic only in early temples (7th–6th century B.C.). Since the second half of the 6th century B.C., the shaft is formed by drums, usually 4 to 9, is tapered and has a swelling

(entasis) at approximately one third of the height. The aspect ratio of the shaft —i.e. the ratio between the diameter at the base, or the average diameter, divided by the height— is equal to 1:4 in early temples, and decreases to 1:6, showing the trend to make the column more and more slender. The top of the shaft is a single block with the capital, with truncate conic or basin shape (echinus), surmounted by a parallelepiped with square base (abacus). Each drum has at its centre a square hole for the insertion of a pin.

Presently, Doric columns show significant decay: crumbling, more or less superficial crazing and macrocracks originated by atmospheric agents. Damage is also present: thin vertical cracks along the shaft and large fractures at the perimeter of the interface between drums originated by impacts induced by earthquakes.

Doric temples: columns with architraves
Metaponto, Paestum, Agrigento, Selinunte

The architrave (epistyle) consists of elements in local stone which join on the axes of the columns. The distance between columns is small in early temples (approximately 1.50 m in the 6th century B.C.), and increases during the maturity of Doric order (2.40 m in the 5th century B.C.). The columns of the façade are placed at a larger distance, so as to emphasize the longitudinal axis of the temple.

The preservation of intact architraves can be explained by the presence of cramps which induce a global motion of the colonnade.

Decay phenomena are present in abaci or architraves, in a way similar to columns. Typical remedies are confinement or reinforcement through iron bars.

Doric temples: colonnades, architraves, friezes, frontons
Agrigento, Paestum, Segesta

The temples better preserved have friezes and frontons.

The frieze, resting on the architrave, consists of triglyphs and metopes and is made of two rows of blocks, inner and outer, in local stone.

The fronton is the triangular wall (tympanum) enclosed by a horizontal cornice and two inclined cornices under the slope of the roof. The tympanum and the inclined cornices often show large cracks and partial collapses originated by atmospheric agents, pollution, wrong interventions and earthquakes.

Doric temples: double tier of columns
Paestum

In some temples (e.g. the temple of Poseidon in Paestum) the cella is subdivided into three naves through two rows of columns with double tier supporting the roof.

ROMAN AGE

Substructiones
Otricoli, Tivoli, Roma, Todi, Pierre Taillée.

Substructiones are structures supporting a horizontal plane in a slope through masonry walls, sometimes connected each other through orthogonal walls, with interposed soil.

Vitruvius proves that the problem of the thrust of the soil on the *substructiones* was well known and states the rules for this type of structures: «The thickness of the masonry shall correspond to that of the soil which is put behind. Then the retaining walls (*anterides*) and the counterforts (*erismae*) shall be built simultaneously. The distance between the counterforts shall be equal to the height of the *substructiones* and their thickness to the thickness of those». Vitruvius only deals with «full» *substructiones*, where the main element is the soil, more or less restrained by masonry walls, connected on the front and without an autonomous covering.

A different type, as much as common, is represented by «hollow» *substructiones*, whose resistance is provided by a set of rooms vaulted in *opus caementicium*.

Thermae
Roma, Albano, Baia, Pompei, Ercolano, Saturnia, Ravenna, Catania

The typical element of thermal architecture is the vault, used to cover different rooms (*apodyterium*,

laconicum, *frigidarium*, *tepidarium*, *caldarium*). The barrel vault is the type most frequently used. Cross vaults are frequent as well and are present in grand size in the Thermae of Titus, Caracalla, Diocletian, in the hall of the Market of Trajan and in the Basilica of Maxentius. Cloister vaults are rather uncommon.

The development of the vault coincides with the achievement of the *opus caementicium*. Frequently, the vault has brick ribs. Several expedients were used to lighten the vault: light inerts for the higher part of the vault, or empty amphorae purposely made and inserted one into the other to form rows incorporated into the casting. Frequently, the heated rooms were covered by a double vault: the countervault was suspended to hooks clamped in the vault forming a hollow space for the passage of heated air.

The problem of the thrust was solved in several ways. Apart from the simplest remedy to enlarge the piers, counterforts were used for both barrel vault and cross vaults. Another remedy was to build smaller vaults near the main vault, so that they counterfort each other. For the domes, the thrust was usually carried by inner counterforts formed by thick walls with large niches. Another way to carry the thrust of domes was to surround the impost by an annular barrel vault.

Frequent types of damage are the collapse of the whole vault or a portion of it, and cracking at the intrados along the meridians of domes. Usually, the degree of damage increases from barrel vaults to cross vaults and domes.

Aqueducts

Roma, Acqui Terme, Tortona, Albenga, Minturno, Spello, Napoli, Termini Imerese

The importance ascribed by the Romans to water supply is documented by the treatise *De acquae ductu urbis Romae* written by Frontinus in 98 A.C. which contains the experience of four centuries. Aqueducts usually tapped springs, even at the cost of lengthening their course. Water flowed inside a channel (*specus*) with plane or vaulted cover, and size such as to be easily accessible for cleaning and repairs. At regular intervals, air intakes restored the atmospheric pressure. The channel, in ashlar or brick masonry, was waterproofed through a thick plaster of *opus Signinum*, a mix of lime, sand, hard stones of small size.

Initially, aqueducts were underground for the whole course (*Aqua Appia*, 312 B.C.). However, when the channel had to cross a valley or cover a plain, it was necessary to support it by arches (*Anio Vetus*, 272 B.C.). The first Roman aqueduct on arches is the *Aqua Marcia*, 144 B.C.: built in *opus quadratum*, it runs on voussoir arches with span 5.10–5.35 m.

The arches are always round and discharge on piers of large cross section with core in *opus caementicium* within masonry leaves. Aqueducts had to be very stiff at the level of the channel, where even small cracks undermined their functionality. However, unavoidably they faced inhomogeneities of the soil which made necessary structural restorations consisting of arches and piers.

Triumphal arches

Roma, Aosta, Susa, Torino, Ravenna, Verona, Trieste, Rimini, Ancona, Ascoli Piceno, Fano, Malborghetto, Spoleto, Spello, Benevento, Pompei, Sepino

The elements of the triumphal arch are: vault, piers and upper block, usually with the shape of an attic, which is the base of the statues. The arch is usually round. The fabric is the *opus quadratum*. For two-faced monuments, placed across a road, the type with single barrel vault is the most common. However, for works of major importance, the type with three vaults is used, with the central vault larger and higher than the side vaults.

Almost never two-faced arches are free standing: they join other buildings like town walls, stadia or aqueducts.

On the contrary, four-faced arches are always free standing. They are complex monuments dating back to the most developed age of Roman architecture (3rd and 4th centuries A.C.). They are located at the crossing of two roads which intersect at right angle, and have cross vaults or domes.

Arches usually have an odd number of voussoirs, with the keystone. There are three types of arches: a) extradossed, i.e. with the extrados concentric to the intrados; b) with pentagonal voussoirs; c) with hammer shaped voussoirs. The connection between different voussoirs is sometimes improved through cramps.

Piers are massive, according to Vitruvius: «When arches are made of wedge shaped voussoirs, piers shall have a larger width so as to be strong and resist when the voussoirs, pressed downward by the weight of masonry, because of their connections, tend to fall at the centre, while at the imposts they thrust outward. Therefore, piers of large size will be able to restrain the thrust and provide stability to the building».

Roman temples

Roma, Tivoli, Terracina, Palestrina, Cori, Pompei, Baia, Assisi, Brescia

From the typological point of view, Roman temples are derived from the Etruscan-Italic models; they are «frontal» buildings, resting on a basement and surrounded by columns on three sides.

The characteristic element of the Roman temple, which distinguishes it from the Greek temple, is the platband, assimilable to the architrave from the point of view of shape, and to the arch from the point of view of structure. However, the platband cannot be used for long spans because its considerable thrust. Platbands may have wedge, hammer or bayonet shaped voussoirs.

A developed version of the platband is reinforced: slots were made in the pulvinos to fit two or three iron bars which carried the tensions at the intrados.

The walls of the cella are made of *opus quadratum* or *opus latericium*, the vaults of *opus caementicium*. The drums of the columns and the elements of the trabeation are made of travertine or marble and are usually connected each other through dogs or cramps inserted in slots purposely made and filled with cast lead.

Bridges

Roma, Rimini, Verona, Padova, Narni, Ascoli Piceno, Spoleto, Vulci, Ferento, Blera, Benevento

The original contribution of the Romans is the arch bridge with multiple spans. The arches are made of voussoirs or masonry. The most frequent shape is the round arch, followed by the flat arch. The spandrels are made of block or brick masonry. The fill of vaults and piers is in *opus caementicium*. The foundation consists of a single platband made of blocks or a bed in *opus caementicium*. Sometimes, the piers are skewed to follow the current, as in the bridge of Rimini and Ponte Milvio in Rome, and provided with breakwater. Typical spans are:

— Ponte Salario, 3 arches, spans: 4.12, 22.76, 4.12 m;
— Ponte Elio, 5 arches, spans: 7.00, 18.33, 18.33, 18.33, 7.00 m;
— Ponte Fabricio, 2 arches, spans: 24.25, 24.50 m;
— Ponte Cestio, 3 arches, spans: 5.80, 23.65, 5.80 m.

The width of bridges is not greater than 7–8 m. The ratio between the thickness of the arch at the key and the span does not follow a precise rule: according to Leger, it ranges from 0.045 (bridge of Narni) to 0.133 (Ponte Fabricio) with average 0.086, calculated on 20 cases studied.

Since the beginning of the 3rd century B.C., the achievement of concrete posed problems of detachment between the leaves and the inner core. Therefore, the voussoirs at the intrados were connected each other by cramps, and the concrete fill was subdivided by inner walls forming several cells (Fig. 3).

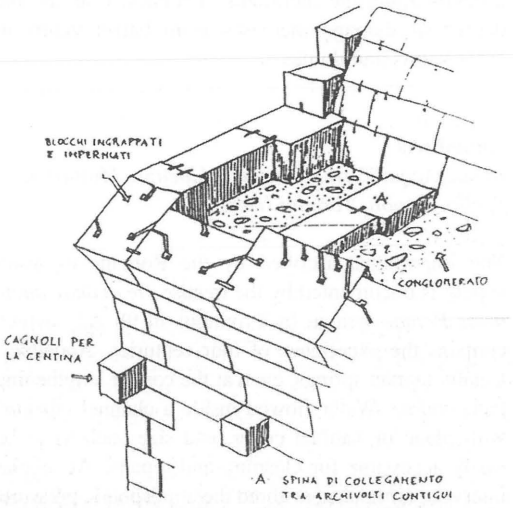


Figure 3
System of connection between blocks, Ponte Cestio, Rome (Giuliani 1990)

Roman theatres

Pompei, Roma, Aosta, Torino, Trieste, Verona, Vicenza, Brescia, Luni, Ventimiglia, Fiesole, Volterra, Pietrabbondante, Alba Fucens, S. Vittorino, Chieti, Sepino, Ferento, Falerone, Todi, Spoleto, Gubbio, Urbisaglia, Villa Potenza, Minturno, Cassino, Napoli, Ercolano, Teano, Benevento, Literno, Scolacium, Taormina

The elements of the Roman theatre derive from those of the Greek theatre, but with significant innovations: the theatre becomes a building, free from soil morphology. Before reaching a complete independence from orographic conditions, since the second half of the 2nd century B.C. up to the first half of the 1st century B.C., the theatre goes through the so called Greek-Roman phase (Fig. 4).

The Roman theatre has its origin in 55 B.C. with the erection of the theatre of Pompeii. The gradin for the audience (*cavea*), has semicircular shape, consists of *ima*, *media* and *summa cavea*, is subdivided in several areas (*maeniana*) and is supported by two or three tiers of arches and pillars. The audience entered through stairs flowing into the centre of each block of seats through purposely made *vomitoria*. Often the *cavea* is surrounded by a sheltered gallery (*porticus in summa cavea*). The orchestra of the Greek theatre, which lodged the chorus, reduces itself to a semicircular area. The stage (*pulpitum*) is raised 1.0–1.5 m above the level of the orchestra. The scene (*scenae frons*) is a structure with two or more storeys, as much high as the *cavea*, with which it forms a single building. The *cavea* is closed at both sides by retaining walls (*analemmata*) parallel to the stage and separated from this by entrance aisles vaulted in *opus caementicium*. Therefore, the Roman theatre is a closed building which only lacks the roof: it could be temporarily sheltered by large sheets (*velaria*).

The elements of the theatres are now in different states: in Roman theatres, the *substructiones* below the *cavea* are preserved, but the latter lacks the gradin; in the Greek theatres of Southern Italy and Sicily, the *cavea* is deprived of the steps, but the shape is clearly preserved. The scene is generally in bad state.

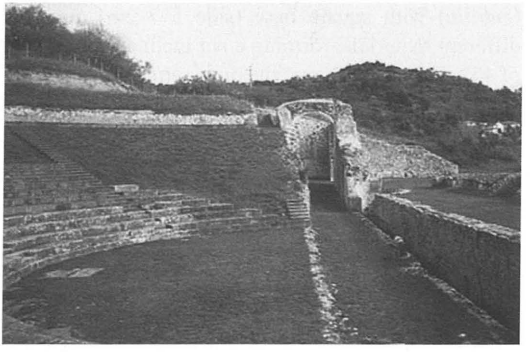


Figure 4
Greek-Roman theatre, Amiternum

Amphitheatres

Pompei, Roma, S. Maria Capua Vetere, Pozzuoli, Cuma, Nola, Verona, Padova, Rimini, Arezzo, Luni, Albenga, Sutri, Ancona, Ascoli Piceno, Urbisaglia, Falerone, S. Vittorino, Alba Fucens, Teramo, Vasto, Tivoli, Tuscolo, Albano, Spello, Spoleto, Otricoli, Terni, Paestum, Grumentum, Venosa, Lecce, Catania, Termini Imerese, Siracusa

Amphitheatres are typically Roman buildings, born to lodge gladiatorial performances.

There are two types of amphitheatres. The former type, on embankment (Pompeii), similarly to the Greek theatre, fits itself to soil morphology, and the gradins rest on the soil retained by walls. An aisle, vaulted in masonry, runs below the first row of seats. The latter type is more strictly architectural and has radial walls with facings in *opus quadratum* or *opus latericium* and concrete fill, connected each other through inclined barrel vaults supporting the *cavea* (Fig. 5). Generally, amphitheatres have two tiers of arcades, sometimes surmounted by an attic with rectangular or arched windows. Few amphitheatres have three tiers of arcades, as the Amphitheatre of Capua and the Flavian Amphitheatre (Coliseum) in Rome.

Often, amphitheatres had to be restored. Restorations were carried out under the Emperors Julius, Claudius, Trajan and Hadrian. Regulations were issued by Tiberius in consequence of the collapse of the amphitheatre near Fidenae. Sometimes, the reason of strengthening was the increase of the audience. Typically, interventions consist of jacketing the annular wall supporting the *media cavea*.



Figure 5
Radial walls with vaults, Amphitheatre, Amiternum

Dwelling types

Roma, Tivoli, Albano, Viterbo, S. Maria Capua Vetere, Pompei, Ercolano, Baia, Pozzuoli, Capri, Piazza Armerina

The *casa insula* is a block of dwelling houses up to three storeys in brick masonry or other cheap technique. It has arches and vaults at ground floor and cantilever balconies.

The *domus* and *villa* are houses with rich and wide illustration of curvilinear architecture.

The masonry types used in dwelling houses, as well as public buildings, can be organized into different classes, based on the characteristics of the stone, initially used for the whole thickness of the walls, and subsequently only for the leaves.

The earliest type is the *opus quadratum*, made of parallelepiped stones. This technique was supplanted by the *opus caementicium*: since the end of the Republic masonry consists of two leaves (*crustae*) and an inner core (*structura caementicia*). The *opus caementicium* was made of scraps of stone or brick mixed with lime, sand and water; therefore, *caementicium* means: «made of *caementum*». This component of the mix had not the modern meaning of binder —taken by the word cement only at the end of the 18th century— but the meaning of «scraps of stones», since the word *caementum* derives from the Latin verb *caedo*, that is «to cut into pieces».

In hydraulic works, sand was replaced, all or partly, by volcanic pozzolan from Baia or Cuma: the property of concrete made of lime and pozzolan to harden under water was well-known, as testified by Vitruvius who provides the instructions for the correct choice of the components and their proportion in the mix. Pliny the Elder and Vitruvius himself recommend to tamp the cast. Roman concrete was similar to modern concrete; the major differences, besides the obvious differences of mix, transport and tamping, regard the type of inerts and binder. In the *opus caementicium*, the role of binder, played in modern concrete by cement, was committed to lime, alone or with pozzolan; the inerts are sand and scraps of stone or bricks, not larger than a hand, as suggested by Vitruvius.

The earliest type of leaf is the *opus incertum*, consisting of stones embedded into the core, with an irregular surface in sight. Alignments on the vertical were avoided, with the aim to prevent cracking. When the leaf was made of cobblestones, it was necessary to insert frequent levellings aimed at smearing the loads on the section. Therefore, since the Augustan Age, horizontal brick belts were inserted into the wall.

At the beginning of the 1st century B.C., the stones become more and more regular (*opus quasi reticulatum*). The subsequent *opus reticulatum* is made of small truncated pyramid-shaped elements (*cubilia*) with square base (side 5–7 cm) made of different materials, forming a net inclined at an angle of 45°. The advantage of the *opus reticulatum* was the standardization of the material. However, Vitruvius trusted the *opus incertum* more than the *opus reticulatum* because the latter required more mortar in the core and was in consequence more compressible, making easier the detachment of the leaves.

The *opus mixtum*, lasting since 50 B.C. up to the end of the 2nd century A.C., is an *opus reticulatum*, with levellings made of horizontal courses of bricks. The subsequent scheme, the *opus vittatum*, initially used in the peripheral regions of Italy, replaces the *opus reticulatum* in Central Italy since the 3rd century

A.C., becomes the most common type during the late Empire, and continues to be used in the early Middle Ages. The leaves are made of square stone tiles arranged in horizontal courses —like bandages, «*vittae*» in Latin— or, in the *opus vittatum mixtum*, alternating stone tiles with courses of bricks.

Brick masonry may be of two types: the *opus latericium*, wholly made of baked bricks, and the *opus testaceum*, with only the leaves in baked bricks. The bricks baked in kiln are the great innovation of Roman building technique. They were made of clay mixed with water and sometimes with sand, straw or fine pozzolan in small amount: the mix was compressed in a square wooden mould with side 20 cm (2/3 of Roman foot or «bessal»), 30 cm (Roman foot or «pedal»), 45 cm (1.5 Roman feet or «sesquipedal») or 60 cm (2 Roman feet or «bipedal»). The thickness ranges from 4 to 2.8 cm, decreasing from the Flavian Age to the Severian Age. The bricks were initially put to dry in the sun, then in a sheltered and ventilated place, and finally baked in a kiln at 800 °C. The porous and lightly rough surface improved the bond with the mortar in bed joints; sometimes, furrows of different shape were made on their surface.

The *opus latericium* was employed for the whole thickness of the wall when high compressive strength was required. A small amount of mortar was used in both bed joints and head joints.

In the *opus testaceum* bricks are cut diagonally to form two triangles, and placed with the diagonal face in sight and the right angle embedded into the inner *opus caementicium* with the aim to improve the connection between leaves and core. A further improvement of the connection was provided by the insertion of bipedals.

Bricks were employed in arches, vaults and discharge arches. The latter are structural, i.e. have the same thickness of the wall, up to two Roman feet. When the wall is thicker, they are limited to the leaves and do not penetrate into the core.

The first example of *opus testaceum* is the House of Tiberius on the Palatine. Since then, it gradually replaces the *opus reticulatum* in urban houses.

Another type of masonry is the *opus Africanum*, employed in Southern Italy and Sicily. It consists of big stone blocks, arranged in the horizontal and vertical directions, with the empty spaces filled by material of small size (Fig. 6).



Figure 6
Wall in *opus Africanum*, Pompeii

A technique employed for popular houses is the *opus craticium*. It consists of a frame in timber beams with square cross section with side 10–12 cm, filled with masonry in *opus incertum* (Fig. 7). Vitruvius



Figure 7
Wall in *opus craticium*, Pompeii

disliked this technique because of its vulnerability to fire, moisture, and cracking at the interface between timber and masonry, but justified it for reasons of rapidity or small carrying capacity of the soil.

Columns with winding staircase

Roma

The Column of Trajan, completed in 113 A.C., inaugurates the monumental type of the free standing column, decorated with a spiral frieze, with an inner winding staircase (Fig. 8). The column is one hundred Roman feet high (29.78 m). The shaft consists of 17 huge drums in Carrara marble, with diameter 3.83 m and height 1.56 m. At approximately one third of the height, the column presents the traditional entasis aimed at improving the optical effect. The spiral frieze was made after the column had been assembled. The decision to make the column accessible through the inner staircase was probably taken after the completion. The connection between the drums is provided, besides the large contact surface, by pins driven into holes purposely made.

On the model of the Column of Trajan, the Column of Marcus Aurelius was erected by 193 A.C.. It is one hundred Roman feet high as well, has diameter at the base 3.80 m and at the top 3.66 m, without entasis. The shaft consists of 19 drums. The third column of the Roman Forum is the Column of Foca, rebuilt in 608 A.C. with earlier materials, probably dating back to the 2nd century A.C.

Columns with winding staircase are different from Doric columns with regard to material (marble instead of porous rock) and size (columns with winding staircase have both larger base and larger slenderness). Presently, they show damage originated by earthquakes, as shown by slidings of the friezes.

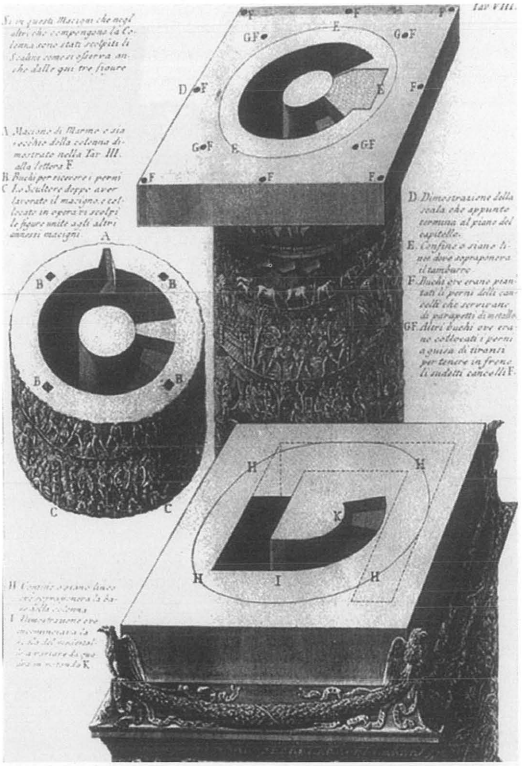


Figure 8
Column of Trajan, Rome (from an engraving by Piranesi)

Conclusions

A classification of types of the Italian archaeological heritage is presented. The classification is centred on the structural behaviour and is the basis for subsequent studies on seismic vulnerability and risk. The study only deals with the types located in earthquake prone regions of Italy, and therefore excludes some types (stone huts and terraced buildings in Lecce area, vault structures in the Salento peninsula, prehistoric nuraghi and holy wells of Sardinia).

Seismic vulnerability is strongly dependent —besides the obvious factors of shape, material and boundaries— on the decay of the materials, hydrogeologic instability, meteorological and climatic conditions, damage induced by earthquakes, work of man.

This study is the summary of the extensive literature on the subject and represents a synthetic reference for further studies aimed at a systematic evaluation of vulnerability.

Acknowledgements

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The XVIIth century: Carlo Fontana's expertises

Gema López Manzanares

Carlo Fontana was an architect and writer who lived between the XVIIth and the XVIIIth century. He was born near Como in 1634 and died at Rome in 1714. He worked for some of the most important architects of the high baroque period: Rainaldi, Cortona and Bernini and he built his principal works in Rome: the Ginetti chapel at Sant'Andrea della Valle; the Cibo chapel in Madonna del Popolo; the cupola, great altar and ornaments of the Madonna de' Miracoli, the church of the monks of Santa Marta; the façades of the church of Beata Rita and of San Marcello in the Corso; the sepulchre of Queen Christina of Sweden in St. Peter's; the palaces Grimani and Bolognetti; the fountain of Santa Maria in Trastevere and that in the piazza of St. Peter's which is towards Porta Cavallegieri. He also built the dome of Santa Margherita in Montefiascone and sent a model for the cathedral of Fulda and to Vienna for the royal stables. He repaired the church of Spirito Santo de' Napolitani and the theatre of Tordinona and sent plans for the Jesuit church and college in Loyola, Spain. His nephews Girolamo and Francesco Fontana assisted him in all these works (Poole, 1909).

Fontana also published works on the Flavian Amphitheatre, the Aqueducts and the inundation of the Tiber. But the most famous work was *Il Tempio Vaticano e sua origine*, a diffuse description of the basilica of Saint Peter, published in 1694 by order of Innocent XI. Fontana included some geometrical rules for the construction of simple domes in this book, and analysed the stability of the dome of Saint Peter's with geometrical and non-scientific tools (Straub 1952; Huerta 1990). These rules were a synthesis of the traditional knowledge about the construction of domes

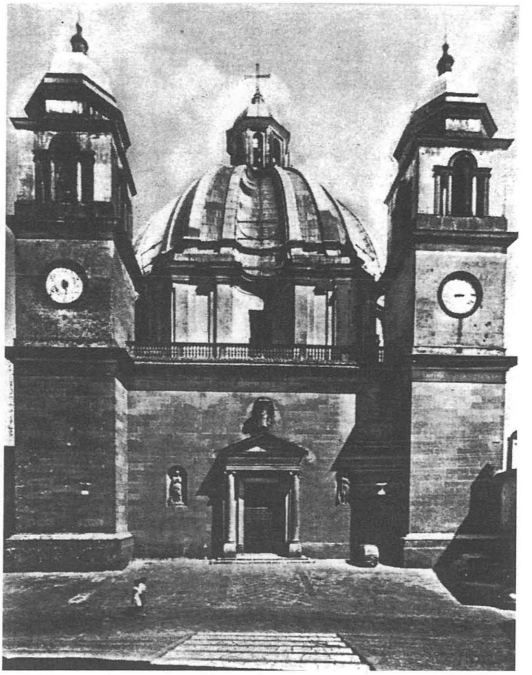


Figure 1
Central façade of the cathedral of Santa Margherita in Montefiascone (Hager 1975)

and were used along the XVIII[th] century. This paper deals with the previous work done by Fontana. He measured several domes at Rome and studied the architectural treatises to find geometrical rules and fixed proportions between the general dimensions and the width of the drum and the dome at the springing and at the top. And he mentioned this work in the context of several expertises about domes (Hager 1973,1975). It is possible to understand the evolution of the thinking of Fontana about the matter and his practical knowledge about the reinforcement of domes and their stability. The influence of the contemporary theory about the construction of domes is also present in these expertises.[1]

The dome of the church of Santa Margherita in Montefiascone

The idea of building the cathedral of Santa Margherita in Montefiascone started at the end of the XV century to provide a bigger and fitting place for Santa Margherita's remains. The works did not start until the beginning of the XVI[th] century, when the famous architect Michele Sanmicheli, superintendent of the works at the Cathedral of Orvieto, was in charge of building the cathedral of Montefiascone. Sanmicheli designed a church covered with a dome, but he finished his project until the drum and the church was covered with an ordinary roof because of lack of money, Figure 2. In 1670 a fire destroyed the roof and the interior of the church. Cardinal Altieri decided to build the dome and so, Carlo Fontana was in charge of building the dome, with 115 palms (34 m).[2]

In 1673 the dome was finished and Carlo Fontana wrote an expertise titled «Dichiaratione dell'operato nella Cuppola di Monte Fiascone colla difesa dalla censura.» He gave two projects, but after built it there were criticism because of the «excessive» width of the dome and the lower part of the church, Figures 3 and 4. The document, written in two chapters, is very interesting, because of the theoretical principles that

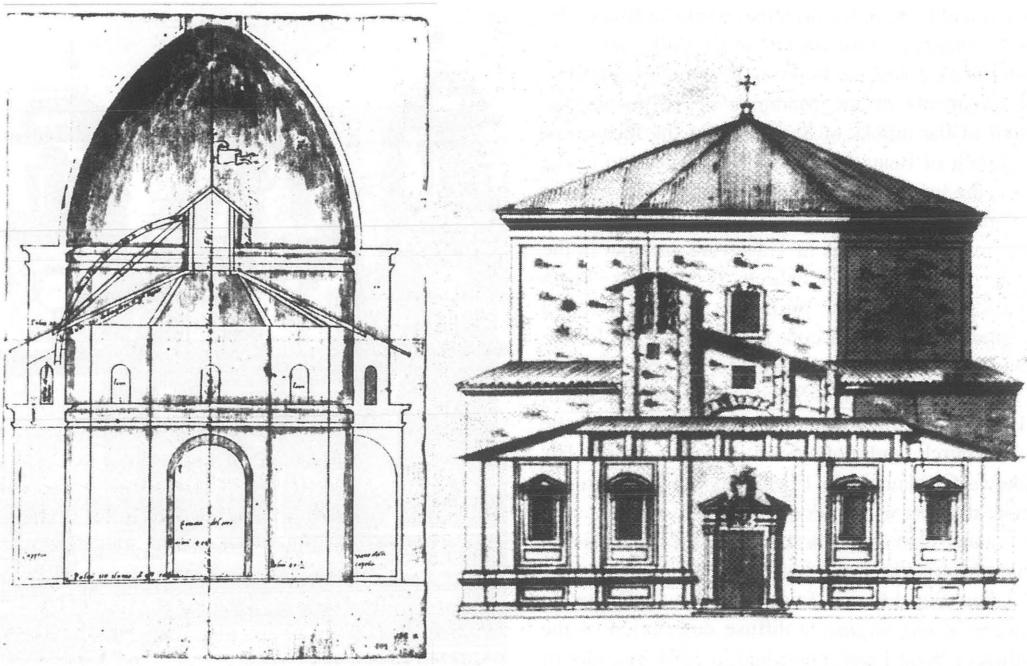


Figure 2
On the left, Meleghino's elevation, building survey and design for the temporary roof of the Cathedral of Montefiascone (Ost 1970). On the right, elevation of the cathedral of Santa Margherita until 1670 (Fontana 1673)

gave the author, mainly in the second part. He tried to justify the dimensions of his project with the measurements of the dimensions of different domes and the geometrical rules or rules of proportion of practical use contained in the treatises.

First chapter

In the first part of the expertise, Fontana explained the first steps he made before designing his projects. He made a survey of the walls and the foundations with the architect Angelo Torroni and the master builder Simon Brogi.

Fontana found that the height and width of the walls were enough to sustain the dome and they did not show cracks. The soil had a great resistance and the small cracks in the church had been caused by the settlements of the masonry elements, natural in this kind of buildings in the first stages of the construction. The old building was safe enough to support the new dome.

After surveying the old construction, Fontana studied the existing domes at Rome, whose proportions he measured «from the bottom, to the Lantern».[3] In the second chapter he will describe these measurements in a detailed way. In this part Fontana described the materials and geometry of the domes. The materials, brick or stone, determined the proportions:

> The domes described, made of brick, indicated me a greater width for the mentioned of Montefiascone, rebuilt with a wall of stone, that for being equal to the brick wall, stronger and with more durability, would have need a double width . . .[4]

Besides the material, Fontana believed that the proportions depended on the fact that there was a drum or the dome rested directly upon the main arches. The dome of Montefiascone would rest upon a drum, while the studied domes did not have drum, so, because of this feature that one would need a double width that he had proposed.

When the first proposal of Fontana was accepted he asked for the «exactness» of the dimensions, because «at first sight one can imagine a different width in the built parts»,[5] Figure 3. In the second and final project, Fontana only made qualitative changes, Figure 4. In this part of the expertise Fontana made interesting

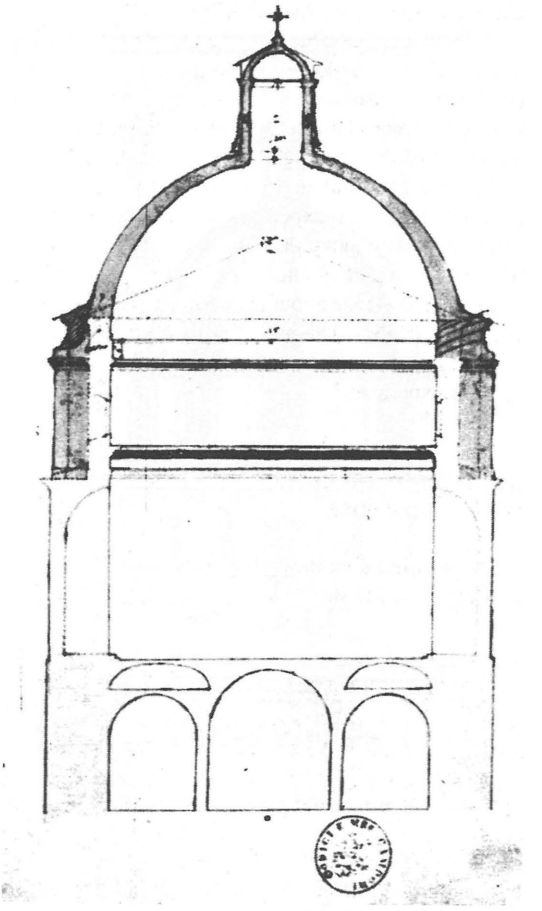


Figure 3
First project of a simple dome for Santa Margherita (Fontana 1673)

statements from the structural point of view. He proposed the construction of eight ribs, «that resist the violence of the winds».[6] There were piers around the drum as a prolongation of the ribs in the dome. A simple cylindrical drum «would be more expensive because of the rings that should be placed instead of the ribs».[7] The niches between the piers were curved, and that was «the reason why they strengthen the whole building and resist the thrust of the dome . . . ».[8]

At the end of the first chapter, Fontana explained that the dome was built with stone because there were no bricks in that area and the building works would

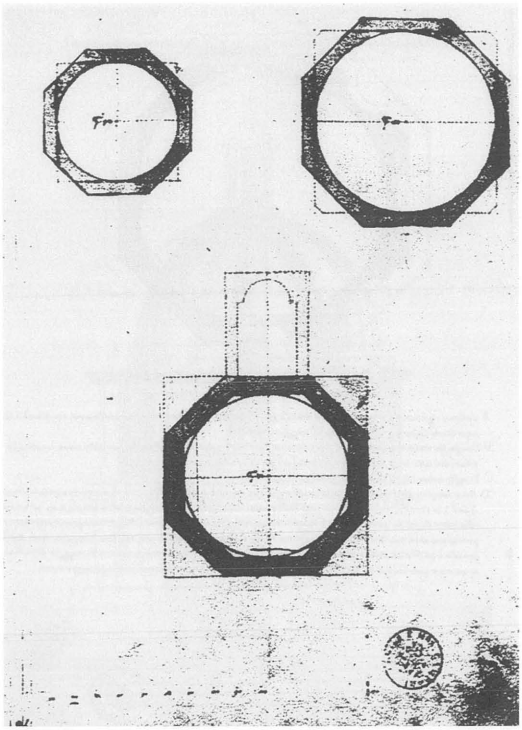


Figure 6
Plans of the domes of Santa Maria Maggiore, Il Gesú and Santa Maria di Loreto (Fontana 1673)

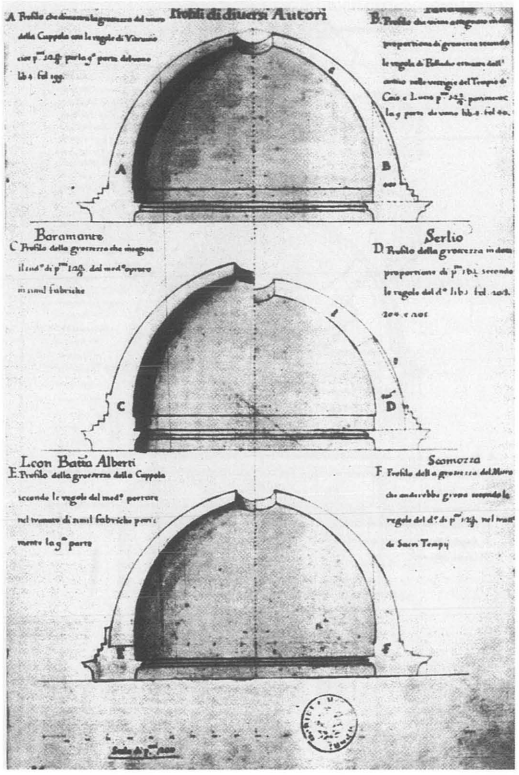


Figure 7
Comparison between sections of simple domes according to different architectural treatises (Fontana 1673)

the width of the base of the dome of Montefiascone if it had been built following each author. The real width of the dome of Montefiascone was always smaller than the dimensions obtained applying the rules of proportion proposed by Vitruvio (1/9), Serlio (1/7), Palladio (1/9), Alberti (1/9).

Fontana made a demonstration based on his own experience and on the treatises that the damages in the dome of Montefiascone were not caused by a bad design or excessive weight.

The dome of Santa Maria in Vallicella, Roma

The church of Santa Maria in Vallicella, known also as Chiesa Nuova, rose on the site of an earlier church called «in Vallicella», because it had stood in the valley of a small stream flowing into the Tarentum marshes. The area was very disagreeable because of the stagnant waters, sulphurous odours and damp mists, and probably there was even a cavernous hole. The pre-Republican Romans thought it covered the Gates of Hell and so, they built a temple in honour of two important underworld deities, Dis and Proserpina. Some of the marbles and statuary of the pagan temple discovered in the XVI century were reused or sold in the new church.

In the XVI century, St. Philip Neri replaced the original Santa Maria in Vallicella supposedly founded by St. Gregory the Great in the sixth century by a new and bigger construction, according to the plans by Mateo da Città di Castello and Martino Longhi the Elder. Gregory XIII and important Roman families helped St Philip to build the church. He

Table1
Proportions of the dome of Santa Margherita according to different domes (Fontana 1673)

Da Carlo Fontana Architetto

				in qualità	in costruttura	
Cuppole diuerse di Roma	*Cuppola di Monte Fiascone*					
Cuppola del Giesu fuori	Di uano p.mi 115 in data	Muro da	nella	p.mi	p.mi	presente
ottangolare dentro tonda di uano	pro portione producono in uirtu	piedi	Cima	15	18	grosso
p.mi 80.g.a p.mi 6 nella cima	delle dette Cuppole le seguenti	p.mi	p.mi $4\frac{1}{2}$	manca	manca	p.mi
p.mi $2\frac{3}{4}$ mattoni	grossezze	$9\frac{1}{2}$	manca p.mi 1	p.mi$6\frac{1}{2}$	p.mi $9\frac{1}{2}$	$8\frac{1}{2}$
Cuppola di S. Andrea della Valle						
Di uano p.mi 78.			manca p.mi		manca	manca p.mi
g.a p.mi			$2\frac{10}{12}$		p.mi $11\frac{1}{2}$	16
$7\frac{1}{3}$ e nella		p.mi	p.mi	p.mi	p.mi	
Cima p.mi 5		$11\frac{1}{2}$	7	20	25	
Cuppola di S. Agnese						
Di uano			manca		manca	manca
p.mi 58.			p.mi $4\frac{1}{2}$		p.mi $13\frac{1}{2}$	p.mi $19\frac{1}{2}$
g.a p.mi 7 nella cima		p.mi	p.mi	p.mi	p.mi	
p.mi 4 mattoni		13	$7\frac{2}{3}$	22	27	
Cuppola della Chiesa Nuoua						
Di uano			manca		manca	manca
p.mi 62.			p.mi $5\frac{1}{2}$		p.mi $13\frac{1}{2}$	p.mi $21\frac{1}{2}$
g.a p.mi 7						
nella cima		p.mi	p.mi	p.mi	p.mi	
p.mi 5 mattoni		14	9	22	30	
Cuppola di S. Carlo a Catenari						
Di uano			cresce		manca	manca
p.mi 72			p.mi $\frac{1}{2}$		p.mi $4\frac{1}{2}$	p.mi 10
g.a p.mi 5		p.mi	p.mi	p.mi	p.mi	
nella cima p.mi 3 mattoni		$8\frac{1}{2}$	$5\frac{1}{2}$	13	19	

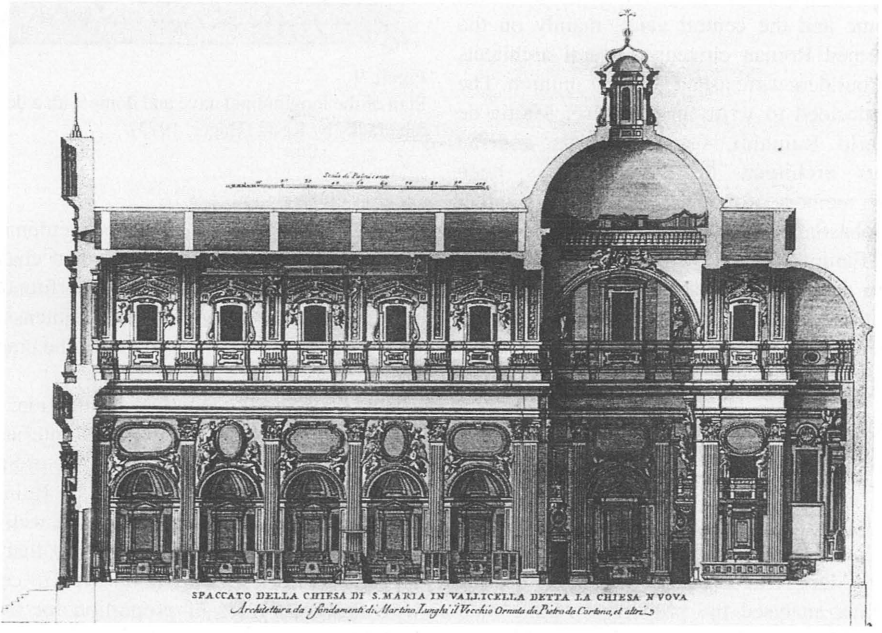


Figure 8
Longitudinal section of the church of Santa Maria in Vallicella, known also as Chiesa Nuova by D. De Rossi in 1721 (Conforti 1997)

fought against illiteracy and used new methods to evangelise children, pilgrims, based on music and Italian language instead of Latin. In Philip Neri's days, the church was known as «the joyous house». Work continued from 1575 until 1583. Faustolo Rughesi completed the façade in 1605.

The Oratorians'church is very similar to other Counter Reformation churches in Rome. It has a Greek cross plan, with a huge hall-like nave, a shallow apse and five lateral chapels, with a double-storied tripartite façade with scrolls.

The dome, which covers the altar, is a hemisphere, with lantern and rests upon a very low drum. Giacomo Della Porta, following the original design of Martino Longhi built it between 1575 and 1599. Borromini put the lead on the roof in 1643. In 1650 Pietro Da Cortona was in charge of the decoration of the inner surface of the church with its paintings, also the inner dome. Da Cortona asked permission for increasing the size of the windows on the lantern to get a better lighting of his paintings. So he built a higher lantern with more weight than the previous one. At the same time he reinforced the dome with a false drum to support the increased weight of the lantern. In 1675, twenty-five years later, the cracks on the dome and the central vault, mainly on the dome, alarmed Roman citizens. Several architects and masterbuilders were asked for their opinion. The architects decided to write an expertise: Mattia de Rossi, Carlo Rainaldi, Carlo Fontana and an anonymous architect. Moreover it has been preserved a memory of the first meeting and another one by Sebastiano Resta where the cracks were described, Figure 9. Finally, a single ring was placed around the dome on the top of the drum and this protected the paintings of Da Cortona that would have disappeared if the dome would be rebuilt.

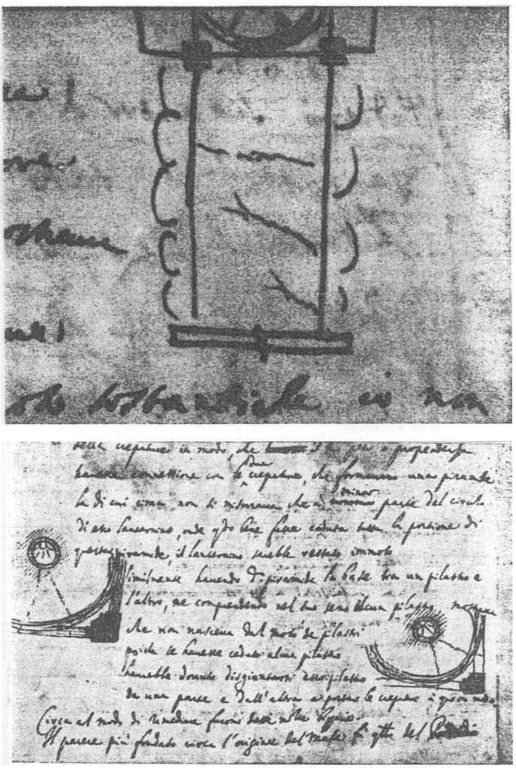


Figure 9
Plan of the longitudinal nave and dome with a description of the cracks by Resta (Hager, 1973)

Fontana's expertise. Analysis of the dome and its proportions

Carlo Fontana wrote an expertise about Santa Maria in Vallicella, two years later than he wrote the one about Santa Margherita in Montefiascone. In the first part, Fontana analysed the proportion of the main structural elements: foundation, piers, arches and dome. The four main arches had not severe damage, so he deduced their dimensions were correct, and that the piers were vertical and without settlement. If not, «these arches would be cracked, and changed their shape».[14] The good condition of the foundation was also a reason to consider that the dimensions of the piers were correct. So, the origin of the cracks was in the dome itself.

Fontana gave quantitative information. As in the expertise about the dome of Montefiascone, he compared the proportions of the dome of Santa Maria in Vallicella with other domes at Rome. So, he measured an insufficient width of the walls upon the dome rested, only 2 palms (0,4468 m), that is, 1/30 of the span, with 65 palms (14,5 m). He compared it with the good rules of proportion for this kind of buildings «the width at the base is usually 1/12 of the diameter, that is, nearly 6 palms and at the top, 1/18 of the diameter, that is, 3 1/3 palms»,[15] Figure 10.

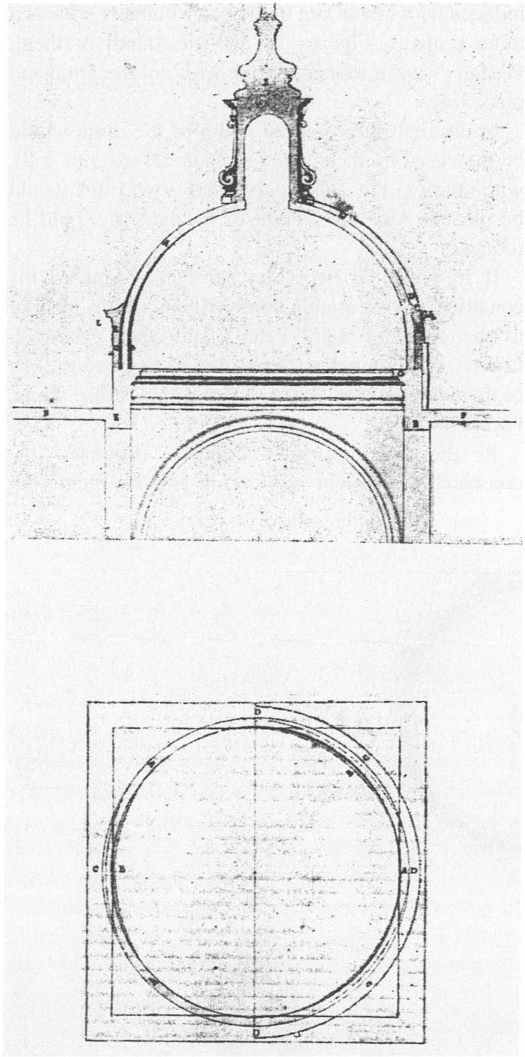


Figure 10
Analysis of the width of the false drum over the dome of Chiesa Nuova rests (Fontana 1675)

Fontana also discovered that the plan of the dome was not a perfect circle, that is, the wall upon which it rested, presented a variable width along the perimeter. This feature and its insufficient width according to the rules of proportion leaded him to state two hypotheses:

1. The builders had little ability, or

2. The project was uncompleted. So the wall looked like no definitive and showed thinner areas, mainly near the façade, also with cracks.

The third origin of the cracks, and more important according to Fontana, was the bad quality of cement, a faulty of execution or that the masonry would have suffered the climate effects during the execution. Moreover, the masonry contained a percentage of cement of 50%.

The lantern and the basement

Although the reasons considered would be quite important to cause damage to the dome, there was another one: the great weight of the lantern compared with the weight of the dome. This weight caused also damage to the lantern's oculus.

On the other side, the supporting wall of the dome, actually a false drum, was weakened by the oval windows. Furthermore, the height of the wall above the springing of the dome was not great enough, because «the thrust acts in the middle o at least at 1/3»,[16] that is, there was no wall in the area where according to Fontana the thrust acted.

The cracks

There were two cracks on the dome, in the nearest area to the façade that tended to converge in the oculus, Figure 9. This sector of the dome had moved from the remaining parts towards outside, and this added weight to the neighborough arches.

Although Fontana did not give quantitative data about the cracks, he observed that they progressed daily. After being painted, the damage had increased double.

The rings

Fontana suggested the conditions to make the repairs effective. The wall must be in very good conditions to put in the chains. Otherwise these could damage the fabric. Fontana distinguished several types of chains by the way of place them and explained their structural behaviour:

> The chains are of different types, so they have a different essence, that is, resistance and stability; laid horizontal or perpendicular, or even oblique, . . . nobody could tell that they are not useful, but depending on the cases and materials.[17]

He also explained that the chains must be placed «in the third of the *Sesto*».[18] But he insisted on the importance of improving the quality of the construction, of reinforcing it in the key places and increasing the width of the drum wall.

Three proposals of reinforcement

Before explaining his three proposals of intervention he explained the way of propping up the dome.[19] Once propped up the lantern the weight could be reduced with no hurting tools. Later Fontana proposed three projects, Figures 11 and 12. In all of them, Fontana wanted to increase the width of the drum and place rings.

In the first proposal, the width of the drum would be increased by means of an octagonal exterior wall, with stairs in the upper part, where two rings would be placed. Also the weight of the lantern would be reduced.

If it would be necessary, Fontana proposed the construction of a double dome with eight ribs, similar to the dome of Saint Peter's and Santa Maria di Loreto, at Rome. Here, he proposed three rings, one of them to be placed in the external shell of the dome, Figure 11.

In the third project, Fontana proposed the construction of eight reinforcing ribs D, Figure 12,

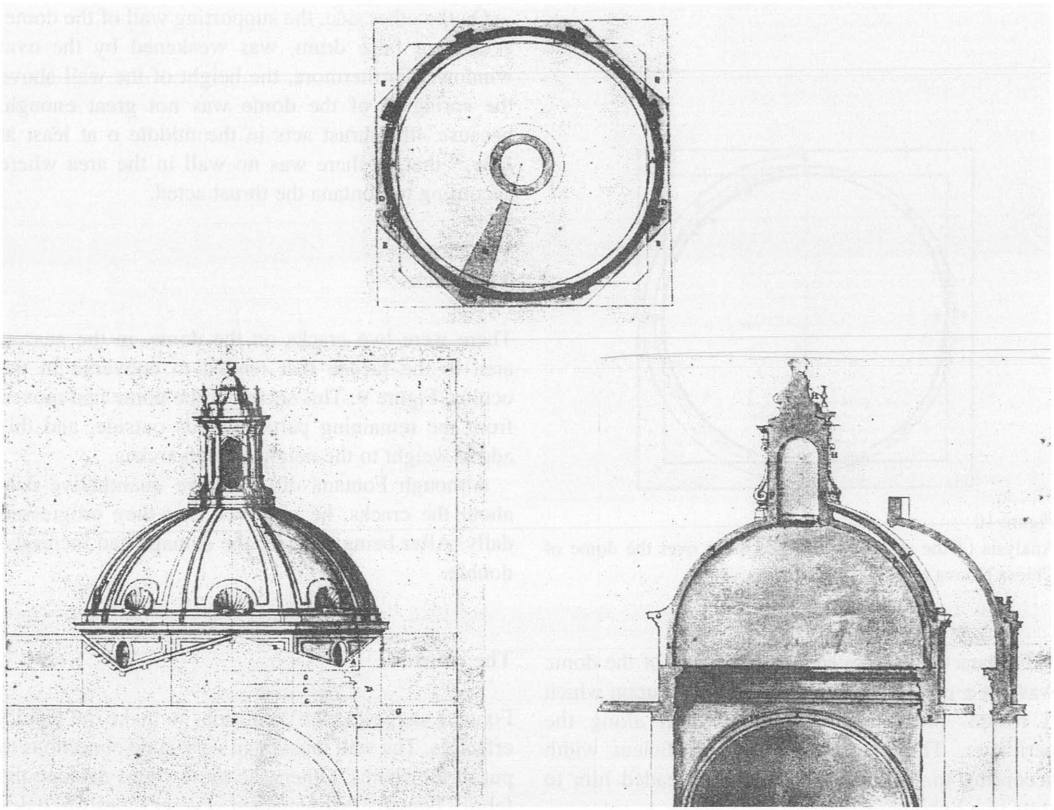


Figure 11
First and second project of Fontana (Fontana 1675)

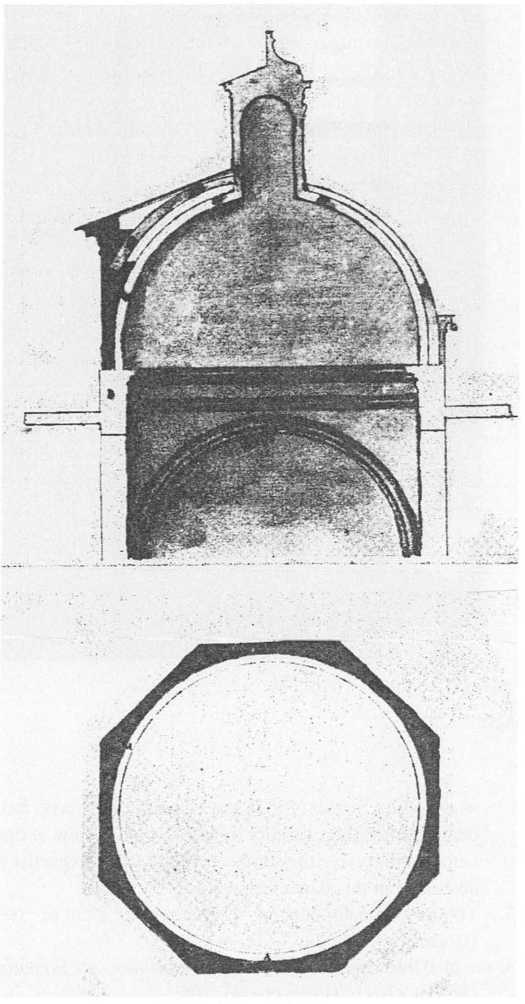


Figure 12
Third project of Fontana (Fontana 1675)

which would transmit the thrust to a reinforced drum «until medium height, where it has a greater thrust, in the *Sesto*, where three rings are to be placed to resist it».[20]

The octagonal drum would be going beyond the springing of the ribs, and this would help counter part the thrusts with its weight. Also the weight of the lantern would be reduced. A sloped roof would cover the dome with the reinforcement.

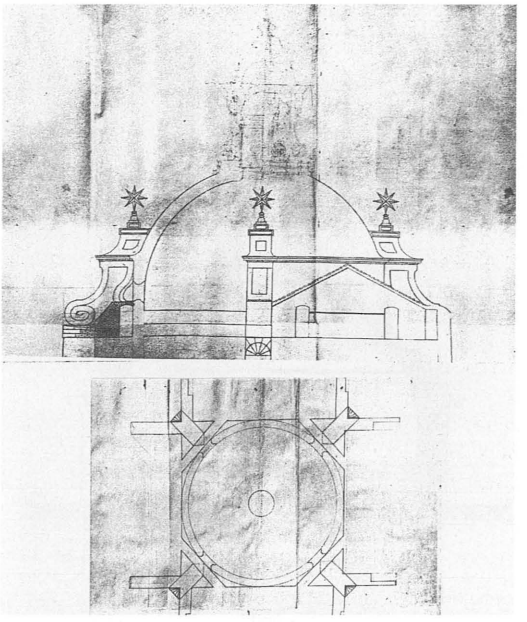


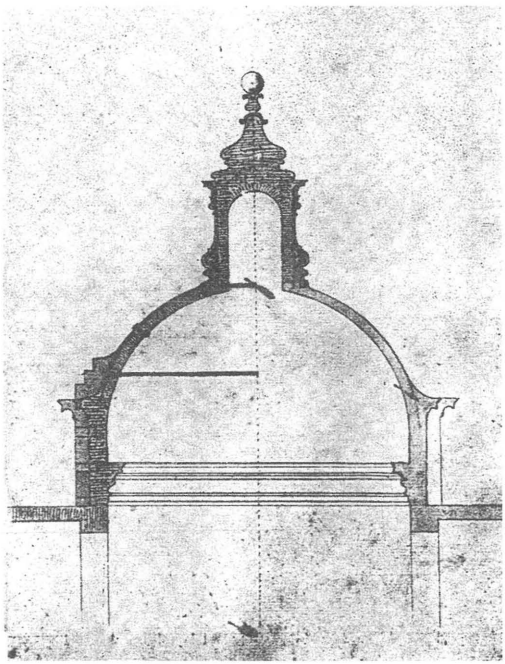
Figure 13
Anonymous project for reinforcing the dome with four buttresses (Hager 1973)

Conclusion

Fontana's rules proposed in *Il Tempio Vaticano e sua origine* would be the final stage of his research about domes that developed along nearly twenty years. His rules were based on the architectural treatises that represented the written tradition about masonry domes, and on his own surveys and measurements of real domes. These rules were not only geometrical, but they were the result of his practical work and they took into account the constructive features of the buildings.

Fontana's expertises are also a proof that the theory of masonry domes developed in connection with the need to study cracked domes and repair them. An expertise is a written document where the architect must justify the safety of a real structure and propose a way to repair or reinforce it, and so we can know now something about the way of thinking in the XVII[th] century about the construction of domes.

Fontana's rules were a link between the tradition and the scientific theories that would be developed



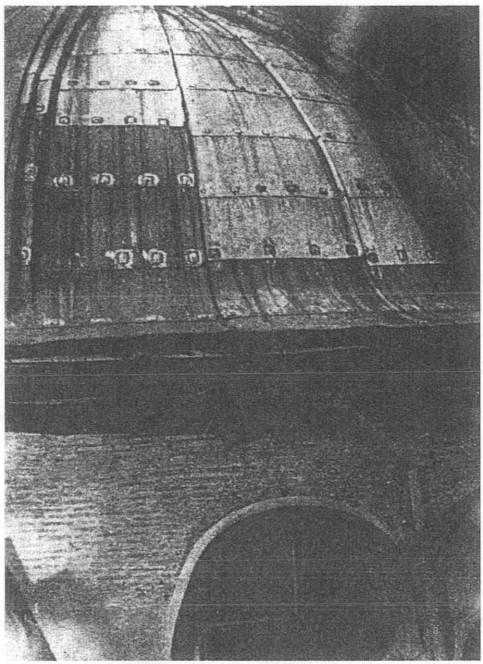


Figure 14
Project of M. De Rossi and the ring placed around the dome (Hager 1973)

during the XVIIIth century and they would serve as practical rules for practicians and theoreticians until the XIXth century.

Notes

1. Only Hager (1973 y 1975) mentioned the existence of these expertises (he reproduced them in his articles), although he did not analyze their structural and constructive significance nor their importance to understand the work done by Fontana about the theory of domes. Falconieri (1695) and later Poleni (1748), who mentioned Falconieri, referred the cases of the dome of Montefiascone and of Chiesa Nuova. According to Falconieri Fontana gave him information about both domes and repaired them with rings, but he did not mention in his manuscript Fontana's expertises nor their relation to Fontana's rules. (Fontana did not mention any ring to place in his own expertise. Perhaps he decided to put the two rings that can be seen today some years later). The rules proposed by Fontana in *Il Tempio Vaticano e sua Origine* (1994) have been analyzed by Straub (1952) and Huerta (1990), who has demonstrated their validity from the point of view of the Limit Analysis theorems. About the expertises described in this paper see also López (1998).
2. The Roman palm contains 12 ounces = 0, 2234 m. See Parsons (1976), 629.
3. « . . .d al loro nascimento, sino al Lanternino . . . » Fontana (1673). Also in Hager (1975), 165.
4. « . . . le descritte Cuppole fatte di mattoni, mi prometteuano grossezza maggiore nella detta di Montefiascone, riformata con muro di Pietra, il quale per uguagliar quello di mattoni, assai più forte, e perpetuo di questo, hauerebbe portato duplicità di grossezza . . . » Fontana (1673). Also in Hager (1975), 165.
5. « . . . che dalla semplice veduta tal uno s'inganna immaginandosi forse diuersità di grossezza nell'operato, dico, che dal primo al secondo profilo, qui accluso restando nella quantità hò: solamente variata la qualità . . . ». Fontana (1673). Also in Hager (1975), 166.
6. « . . . che repugnano alla violenza de venti . . . » Fontana (1673). Also in Hager (1975), 166.
7. « . . . che hauerebbe portato spesa maggiore per uoler colle catene ottener l'effetto, che partoriscano li Costoloni.» Fontana (1673). Also in Hager (1975), 166.

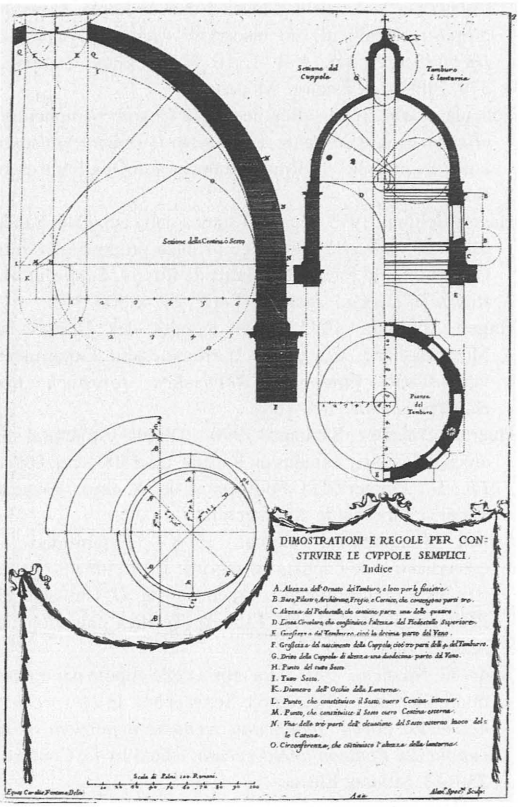


Figure 15
Geometrical rules for the construction of simple domes (Fontana 1694)

8. « . . . per la qual causa partoriscono vigore al corpo della Machina, e contrastano col spingimento della Cuppola, hauendo attiuità basteuole per la proportione del Muro tolta dal vano delli finestroni, e portata al viuo delli detti Pilastroni, li quali così assicurano l'Arco in virtù della lor grossezza.» Fontana (1673). Also in Hager (1975), 166.
9. This stone was volcanic and so, lighter, according to Marconi (1997), 231.
10. « . . . pelo perpendicolare alto p. mi. 12 in circa . . . » Fontana (1673). Also in Hager (1975), 166.
11. « . . . trauersali, et irregolati . . . » Fontana (1673). Also in Hager (1975), 166.
12. « . . . Io non mi sia allontanato dalle regole di Vitruvio, Palladio, Vignola, Scamozzi, Serlio, e Leon Battista Alberti.» Fontana (1673). Also in Hager (1975), 166
13. I have deduced from these dates that Fontana increased the width of the wall in two thirds to take into account the material, brick, and later in one fifth to consider the drum. So the final width of the wall at the springing would be twice the width deduced of the rule of proportion of each dome. The real width of Montefiascone was smaller than these quantities and so the dome lighter compared with the traditional rules. In 1694 he established the width of the dome at its base as 3/40 of the span and advised the architects to build the drum of the simples domes made of brick with a width of 1/10 of the span, and the domes made of light stone, with a width of 1/9 of the span, like in Montefiascone's drum (already built when Fontana was in charge of the project of the dome). This means that he reduced the width that the treatises advised for the base of the dome (1/9 of the span to 3/40) and proposed lighter domes with a modified profil or structural elements like the ribs.
14. « . . . che nelle tangenti della Cornice come parte più debole, & loco della Diuisione delle Quattro forze, si trouano saldi, e senza motiui di peli considerabili . . . si uedrebbero aprire detti archi, riducendoli fuori del proprio Sesto . . . » Fontana (1675). Also in Hager (1973), 314.
15. « . . . sogliono esser le lor grossezze nel nascimento circa la duodecima parte del Diametro, cio è palmi 6. scarsi, e nel finimento la Decima ottaua parte del medemo cioè Palmi 3 1/3 . . . » Fontana (1675). Also in Hager (1973), 314. Fontana referred to the width of the dome at the springing, not to the width of the drum.
16. « . . . lo spingimento è fra la metà dell'eleuatione, ò almeno il 3.o . . . » Fontana (1675). Also in Hager (1973), 315.
17. «Sono Catene di varij Generi; onde diuersificano nel loro essere, cio è fermezza, & immobilità poste Orizontalmente, ò perpendicolarmente, o uero obliqui, non si nega, che ogn'uno di questi non possa fare qual che effetto, mà secondo i Casi, e le Materie.
In che venendo alle Catene, due forze da loro si riceue, che sono mantenimento, e solleuamento, pur che ui sia fermezza nelli dui punti principio, e fine, secondariamente ui è poi la Circolare, che in se costringe nel proprio luogo un corpo sferico.
. . . e le Oblique sono aliene delle dette due forze, cioè Perpendicolare, e Orizontale in ordine al suo proprio genere, sono fuori delle terminationi rette, per essere parte di un Circolo, come materialmente si uede da un pezzo di un Cerchio di qualsiuoglia materia premendolo nelli due lati, ò punti, s'inarca, e stirandolo si adrizza, Dunque concesso, che sia costituito sopra una base soda, e eretta in eleuatione la parte piegata attenderà sempre al suo Centro, e si renderà nella Cima immobile.» Fontana (1675). Also in Hager (1973), 315.

It could be deduced from these words that Fontana meant the rings exert centripetal forces because of their circular shape. So, when their position is completely horizontal they are not able to resist vertical forces, mainly when the weight is too big, as it is the case of a horizontal ring put around the base of the lantern.

18. « . . . nel terzo del Sesto . . . » Fontana (1675). Also in Hager (1973), 316.
19. «Sarà necessario fare il Ponte Reale alle imposte della Cuppola di dentro con corde abbili à sostenere le incavallature Zoppe, che anderanno à ferire sotto il Lanternino per riceuere sopra di se il proprio peso per diuertimento nella propria cuppola, acciò concedi più facilmente la perfetta operatione di ritorno, sopra le quali con uarij sbadacci, ò forze Diagonali, che medemamente anderanno à ferire doue sono le parti relassate.» Fontana (1675). Also in Hager (1973), 316. From the text of the expertise it is possible imagine a propping system with tension and compression members.. The propping system would make possible to survey the drum.
20. «C. Refianco quasi a mezza eleuatione, doue fa la maggior forza nel Sesto, nel quale ui si pongono tre Catene per resistenza della medema.» Text from the figure 12. *Spaccato del progetto per ridurre il peso della lanterna e di sostenerla con otto sostegni (D) fondati su un tamburo ottagonales da costruire e nascosti sotto un tetto pendente.* Fontana (1675), Fol. 41. Also in Hager (1973), 310.

Note

This paper belongs to the research program of the Universidad de Alcalá de Henares

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Extradosed vaults in the Monastery of El Escorial: The domes at the church towers

Ana López Mozo

The analysis of ashlars vaults at the monastery of El Escorial shows that a great effort was done in research and development since the beginning of the construction work, in what finally became a definitive contribution to the introduction of the formal Renaissance repertoire in the Spanish architecture. Complex constructive tasks were carried out, i.e. the realization of low profile and planar vaults,[1] and extradosed domes. Before the monastery was built, the examples of extradosed vaults, i.e. the type of vault in which the internal shape, materials and quartering are recognisable in the exterior, were very scarce, and even more of those built on tambours (Bustamante and Marías, 1982, 8, 103). Juan Bautista de Toledo, the first architect of the monastery, who had worked with Michelangelo in Saint Peter's, died twelve years before construction work on the dome started, so his followers had to carry out tasks in which they had little previous experience. In the building we are studying, several extradosed vaults on tambours can be found: the dome of the church and those of its towers (figure 1).

The study of an extradosed vault is especially interesting as it gives the added possibility of analysing the external face as well: a precise survey in which there is a direct relationship between intrados and extrados permits the geometry of the whole section of the vault to be studied, and an analysis of the quartering to be made, proposing a hypotheses on the constructive configuration. The aim of this work is to approach the domes of the towers of the church at the monastery in El Escorial to know something else about how they are, how they were built and why certain decisions were made. On the other hand, the content of this paper is part of a doctoral thesis on the vaults of this building.[2]



Figure 1
Dome and church towers at the monastery of El Escorial

The towers and the dome: the same idea

The analysis of the church towers is fundamental in the study of the vaults of the monastery, as they are part of a whole together with the main dome: on the one hand, though in a very different scale —the internal diameters are 6.68 m and 18.94 m

respectively— the same constructive and formal problems are posed and solved. In both cases, they are stone extradosed vaults on cylindrical tambour with spherical surfaces in the extrados and intrados, finished in a lantern.

On the other hand, the three domes were built almost at the same time. The conditions and budget to carry out the works of the main dome are written by Juan de Minjares, clerk of the work of the church, on November the 12th 1579. Five days, on November the 17th this party is contracted; the works of the bells towers are contracted on the same day, being Juan de Minjares also in charge of the writing of the conditions, what he did the day before (Bustamante, 1994, 494–497). Francisco del Río and Diego de Cisniega, who later were responsible for the space under the choir place, were in charge of the southern tower and Juan de la Puente and Lope de Arredondo of the northern one.

On January 1580 two wooden cranes are finished and placed to work in the carpentry of church towers (Bustamante, 1994, 498). On July, the eight initial cranes for the dome are also placed and the towers ones are elevated 40 feet (Bustamante, 1994, 498). The works in the southern tower go faster than those of its twin (Bustamante, 1994, 501).

On September 1581, the centrings of the three domes are placed (Bustamante, 1994, 501). Both towers are finished by December 1581: on the 22nd the works are measured and described (Bustamante, 1994, 503).

The works in the dome go slower, but by March 1582 they must be near the end as the carpenter is told to dismantle the cranes of the dome, the centring of the large *half-orange* and the lantern scaffolds. José de Sigüenza points out that on June the 23rd 1582, the fabric body of the church was finished and the cross was placed on top of the dome (Sigüenza, 1602, 147).

Existing graphic documentation

The existing graphic documentation of the church towers is wide and very worthy, despite the fact that no section drawing has been found, what is basic for the realization of this work, nor of the vaults quartering.

Among this documentation, following a chronological order, there is an elevation of the towers in the well known C section, supposed to be by Juan Bautista de Toledo, which shows an state of the idea very far away from the final result. The drawings by Juan de Herrera of 1579 include several floor plans and a complete elevation in which outstands the treatment of the extrados of the dome and the lantern proportion, to which the size of the external sphere should be also added. In the drawings by Herrera for the *Estampas* printed by Perret, the dome still appears with projections in the extrados, as probably they would have liked to build; however, in the budget conditions by Juan de Minjares, no reference to that projections appears, though there is neither any reference to the interior ones, which in fact were built (Bustamante, 1994, 496).

There are also available a number of detailed drawings of the survey by José de Hermosilla, on 1759 (Marías, 2001): the towers appear in an elevation with great fidelity to the actually built, except for the height of the lantern and the finial which appear with some exaggeration. On the other hand, the survey and analysis carried out by Ortega are also available, whose consultation has been of great importance for the realization of this work. In his drawings the tower appears described in two plans and a complete elevation (Ortega, 1999).

Survey

The survey was done on the southern tower. The measurement of inaccessible areas was carried out with a laser survey station and those of the interior in the two levels of the lower body were done manually with tape and laser measure.[3] The work at the monastery with the laser station was partially done with Miguel Ángel Alonso Rodríguez.

The cloud of points located by the laser station determined all architectural shapes and joints of the vault quartering. It was necessary to take data from several station base points that were merged afterwards in the same coordinate system locating sharing points between at least two bases. The points were then processed and analysed in a single digital file, where all the drawings that are showed in this paper were done (figure 2).

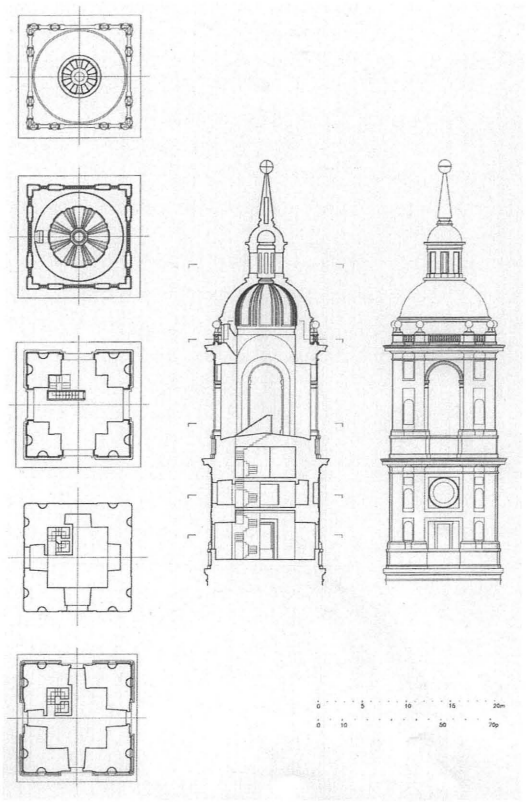


Figure 2
Plans and sections of the southern tower

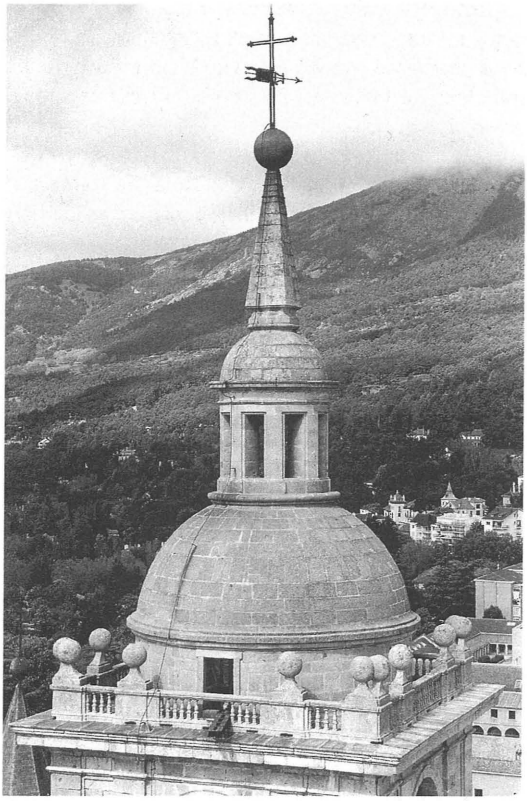


Figure 3
Southern church tower at the monastery of El Escorial

Geometric configuration and quartering

The top of the bells body in the church towers is formed by a hemi-spherical extradosed vault on cylindrical tambour laying on pendentives in the interior and finished in a lantern and finial (figure 3).

The intrados of the dome is formed by an elevated hemi-sphere 25 feet diameter with projections. In the external face another sphere with different centre with respect to the previous one and virtually tangent to the laying tambour forms the almost *half-orange* (figure 4). The main projections are sectors of a 24 feet diameter sphere and the secondary ones are sectors of a 24.5 feet one. These three spheres are not concentric: the height of the centre increases as the radius decreases. In this way the thickness of the projections reduces as it approaches the centre of the dome and equally the width decreases given the fact that they are radial sectors.

In the exterior sphere and tambour have the same diameter: 36 feet. The measures obtained for the thickness of the dome are clearly smaller than the ones reflected in the budget (Bustamante, 1994, 496). The hollow configuration of the finial is described in the expert valuation of the finished towers (Bustamante, 1994, 503).

The section of the dome of the tower has been compared to the one of the main dome. For that purpose, on the left side of the drawing showed in figure 5, the section of the dome of the tower (line) and the section of the main dome (shadowed) have been represented in different scales, to obtain the same center and radius of the external sphere. As can be seen, the section of the dome of the tower is

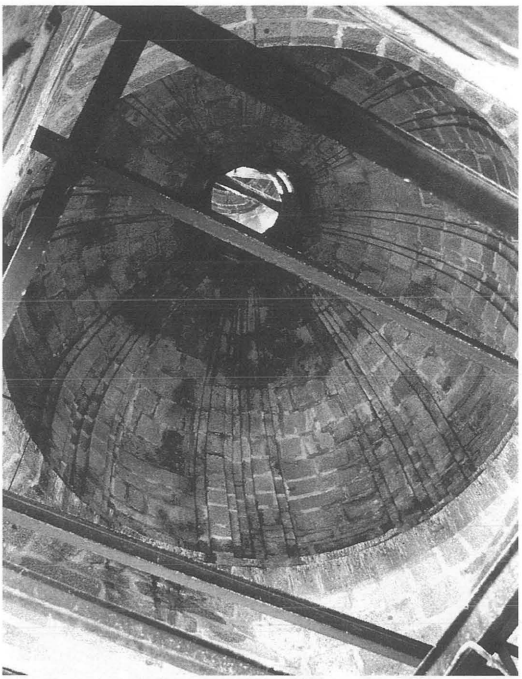


Figure 4
Intrados of the dome of the southern church tower

proportionally thicker. On the other hand, on the right side of the same drawing a proposal of what could have been Herrera's idea for the section at the moment in which he was drawing the plans and elevation of the tower (1579), is represented. For that purpose, the elevation profile has been copied and an intrados has been proposed with a diameter that is a figure that Herrera gives in the interior length of the square of the plan of the bell's body. The diameter would be 29 feet instead of the 24 actually built and could concluded that the dome that Herrera had in his head initially was much thinner, with a proportion similar to the main dome. On the other hand the relationship between the actual exterior diameters of the main dome and those of the towers is 2.27:1.

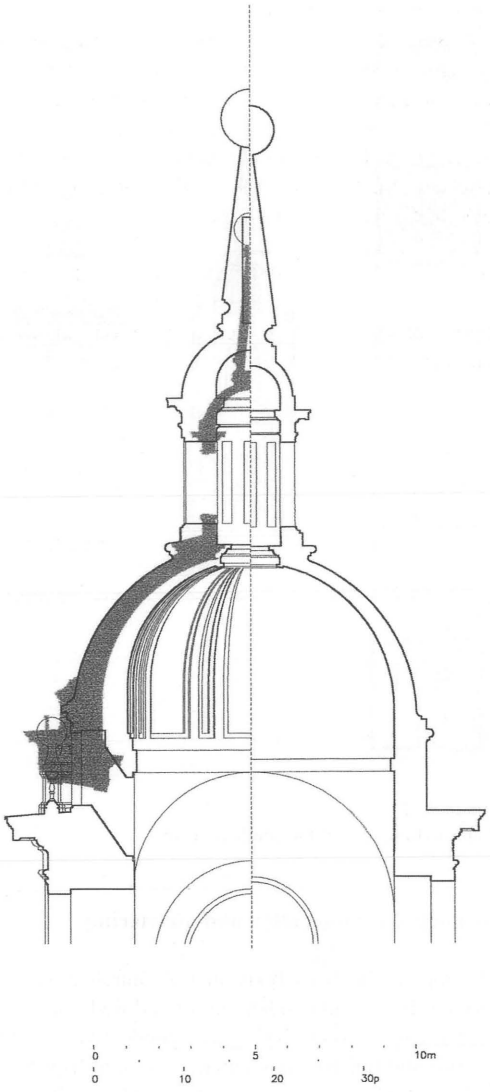


Figure 5
Analysis of the tower dome section

Hypotheses on constructive configuration

A simple visual inspection of the exterior quartering of the dome of the towers reveals, following Enrique Rabasa (2000, 162–167), the existence of a course significantly higher than the rest: his reasoning about a change in the beds disposition in that course, which would be radial instead of horizontal, has guided the direction of this and other works.

The dome is formed by an ashlars double sided structure in its lower part; the internal and external

radial joints between voussoirs in the same course do not coincide in any point, not even taking into account small deviation in carving or posing. From the high course previously mentioned the coincidence in the radial joints is complete what leads us to think that there is a single sided structure. This proposal coincides with the way in which the dome was budgeted (Bustamante, 1994, 496). The proposal of beds configuration in the area of the vault in which there is a single-sided structure is immediate just joining, in the section drawing, the points which define each external course with its corresponding internal one (figure 6). The prolongation of this lines coincides very accurately with the center of the internal sphere. On the other hand the slope in the beds of the projections confirms this posing.

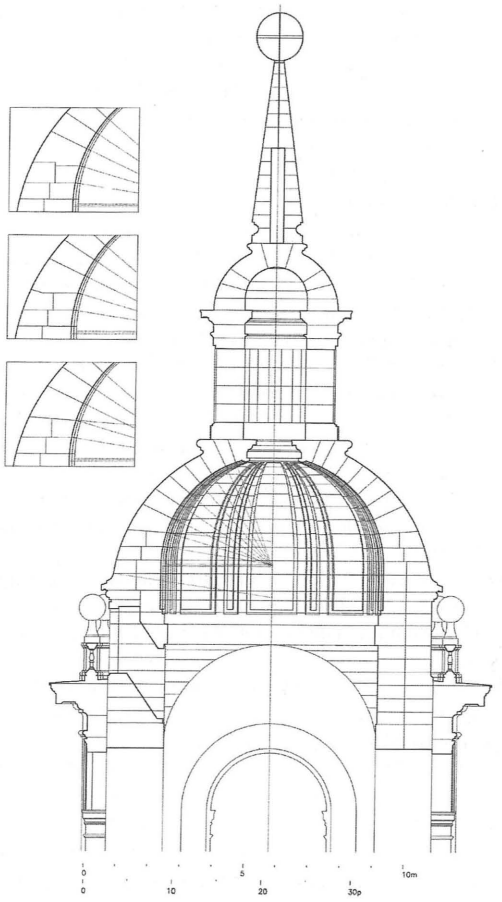


Figure 6
Hypotheses on constructive configuration

The first six courses, counting from the dome's internal elevation, are organized in horizontal beds; the seventh one would be the high course whose over-bed would be a little bit sloped, but not in a radial way and it would also be the piece of change, with more height in the extrados to avoid to finish too narrow in the intrados. In the drawings of figure 4, on the left side, three hypotheses, which could be valid for the support of the high course, are posed. In the immediately previous course, the inclination of the bed and the over-bed in the projections is different than that marked by the voussoirs of the plain areas, in a radial organization following the centre of the sphere of the main projections. Thus, in that course , the beds have an inclination that changes when *leaning* over the projections.

The described configuration poses that the dome was started to build by horizontal beds, with no need of centrings, for the successive projecting of the pieces. From a certain point, and now with centring, the construction was completed with radial beds after organizing a higher transitional course between the two constructive systems.

The confirmation of this constructive disposition in the dome of the tower could permit to propose a new reasoning line for the quartering of the main dome (Alonso and López, 2002, 303–308): the inclination of the beds in the lower part of the projections does not imply that all the voussoirs of the same course have to follow the same pattern, especially where the external side is organised in horizontal beds and a centring would be needed for the interior (figure 7). On the other hand, the analysis of the high course in this dome poses new questions: as it is still formed by a double sided vault, it would permit to organize two normal size courses in the external side, instead of just one. Perhaps it could be possible to pose that these large pieces work like belts, in an area in which the push has very little vertical component and the existence of a horizontal bed could make the voussoirs to slip.

The aim of this work was to know something else about the domes of the church towers at the monastery in El Escorial. A proposal on how the towers are has been made; a number of hypotheses on its constructive configuration, where no verification is possible, has been established, and finally many

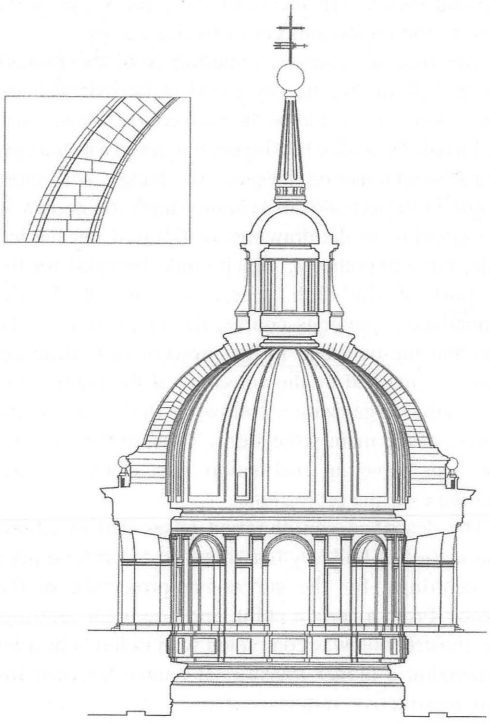


Figure 7
Church dome at the monastery of El Escorial. Survey by Miguel Alonso Rodríguez in cooperation with Ana López Mozo; in the box, her alternative proposal for the constructive configuration of the dome

question marks on the history of this elements and the events that took place around them have been opened: Why the dome changed so much from Herrera's drawings? Was its thickness increased for

the change in the lantern proportion or is there any other reason? Why the dome was budgeted without projections, Herrera draws it with external ones and finally it is built with internal projections which can be seen only from the interior of the bell's body? The domes of the towers could have been somehow models of the main dome in a ? scale: really new formal and constructive configurations which were going to be used very rapidly in the main dome, were tested there.

Notes

1. The analysis of these two planar vaults has been approached in a different paper for this congress, titled «Planar vaults at the Monastery in El Escorial».
2. *The vaults of the Monastery in El Escorial,* carried on by the author of this paper guided by Enrique Rabasa Díaz, professor at the Madrid School of Architecture.

Part of the content of this paper was presented at the symposium *The monastery of El Escorial and architecture,* which took place at El Escorial on September 2002. Another paper on the same subject was presented by Miguel Ángel Alonso Rodríguez, titled «About the towers domes at the Basilica of the Monastery of El Escorial».

3. The realization of this surveying has been possible due to the availability of the measurements instruments of the Department of Graphical Architectural Ideation of the Madrid School of Architecture, specially the laser surveying station, and also due to the kindness of the National Heritage Office at El Escorial, permitting all the visits needed to complete the fieldwork.

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Planar vaults in the Monastery of El Escorial

Ana López Mozo

Those involved in the construction of the monastery of San Lorenzo in El Escorial faced the challenge of building Renaissance shaped ashlars vaults. In accordance with this intention they abandoned the rib and panel Gothic vaulting, making in any case non-structural ribs as in the church dome and intrados of the towers. They got to build in the Prince's Pantheon some vaults with an external Gothic appearance, which does not actually consist of a self-resistant framework of ribs supporting light panels.

The study of the monastery basement is especially interesting: there are splendid and *strong* vaults that solve the covering of these rooms with a considerable span and low height structure. Because of the height limit, a wide repertoire of basket arches was tried and a search on low profile vaults was began. On the other hand, the sail vault type was profusely employed developing amazing solutions for quartering, in spite of its location in service rooms.

A good example of this design and construction effort can be found in the planar vault made by Juan Bautista de Toledo in the basement, under the initial king's room, in the middle of the southern façade, in the place of the discarded Noon Tower. It is an almost square plan room with a central column supporting four arches. A planar ashlars vault with rounded quartering rests on the arches and four smooth pendentives solve the corners.

Some years later, the planar vault designed by Juan de Herrera under the church choir place (figure 1), meant the zenith of the work on low profile vaults made at the monastery: four main basket arches support a vault which shape has a lot to do with the former mentioned one, with pendentives between the arches and the central planar area.

The aim of this paper is the study of the two mentioned planar vaults, in order to find out something more about how they were built and why certain decisions were made. This work consists of analysing geometry and quartering to pose hypotheses on its constructive configuration and initial tracings. Concerning Juan Bautista de Toledo's planar vault, this work tries to find out something else about the central column and whether it was made

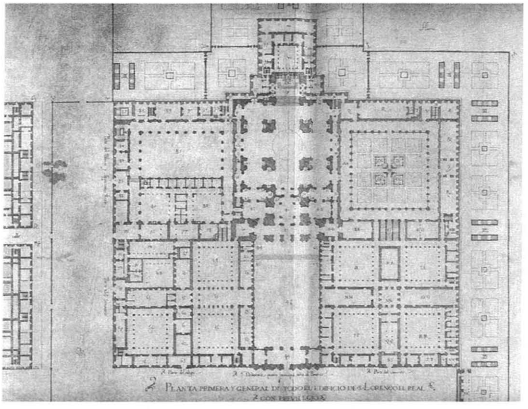


Figure 1
First drawing from the monastery *Estampas*

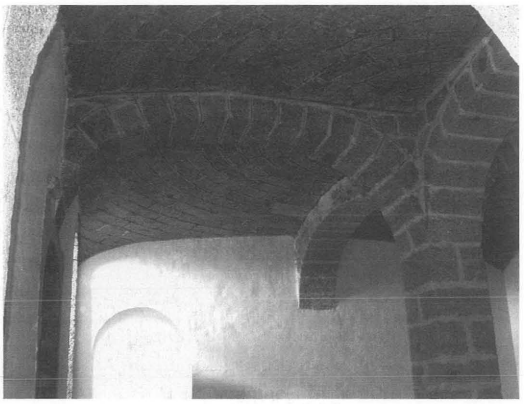


Figure 2
Planar vault in the monastery basement, under the discarded Noon Tower

from the beginning or not. On the other hand, this work is part of a doctoral thesis about the vaults of the Monastery.[1]

An accurate surveying was specifically carried out for this work, in order to provide reliable data of both vaults. The measurement was done using a laser surveying station,[2] locating a cloud of points —4892 from the *under choir* place and 2032 from the basement planar vault— determining all architectural shapes and joints of the main vaults quartering. It was necessary to take data from several station base points in both areas that were merged afterwards in the same coordinate system locating sharing points between at least two bases. The points from each area were then processed and analysed in a single digital file, where all the drawings showed in this paper were done.

The planar vault in the monastery basement, under the discarded Noon Tower

The first planar vault built at the monastery (figure 2) is located under the initial king's room at the back of the initial church. These rooms are indicated with letters HH and GG in Herrera's drawing in figure 1, and it is a single space at present time, known as the *old church.*

The first mass celebrated at the monastery took place in the initial church on March the 8th 1565 (Villacastín, 1595). Floor centring for the church choir place, just over the king's room, were being placed on January 1566 (Bustamante, 1994, 114); as they should lay on the planar vault we are concerned on, we could think that it was finished at the end of 1565. The work in this area goes on slowly from this moment, in spite of that the king wished to have his room ready as soon as possible: it is being paved on February 1567 (Portabales, 1945, LXIV), almost one year after the beginning of its ceiling centring. Though it may sound strange due to the lack of any reference or document, could a problem arise in the planar vault which made convenient its loading on the central column and the four arches which can be seen at present, being this the cause of the delay in the works of the upper floor? In any case, the vault was built before the death of Juan Bautista de Toledo on May 1567, and the clerk in charge of it could be Lucas de Escalante, who was also responsible for the works of the initial church (Portabales, 1945, LVI).

The drawings of figure 3 describe the current state of the room covered by the planar vault. The plan is almost square (30×31 feet) and it is one of the scarce spaces in this area with a direct access from monk's garden. A square column with 2.5 feet length, decentred with respect to the symmetry axis of the room supports four basket arches of which the design follows the pattern described by Alonso de Vandelvira; the arch which lays on the southern façade loads, amazingly, on the entrance transom. The arches support the vault, approximately 1.5 feet thick,[3] and an intermediate filling can be appreciated between one of the arches and the vault.

In the above mentioned drawings of figure 3 the vault has been strictly represented in its current state without adjusting it to any theoretical geometry or false symmetries, in order to appreciate what could be great deformations. In the intrados there is a central planar zone —with a certain descent in the middle— which does not reach the walls; an intermediate ring starts a smooth transition to the pendentives. In the intersections of the vault with the loading walls, we find four non circular arches. Three out of the four quadrants of the vault show single trace rounded courses, centered in the intersection point between the symmetry axis of the room; in the south-eastern quadrant, the courses are also rounded, but with a displaced center with respect to the previous one and with a more irregular trace for the radial joints. A

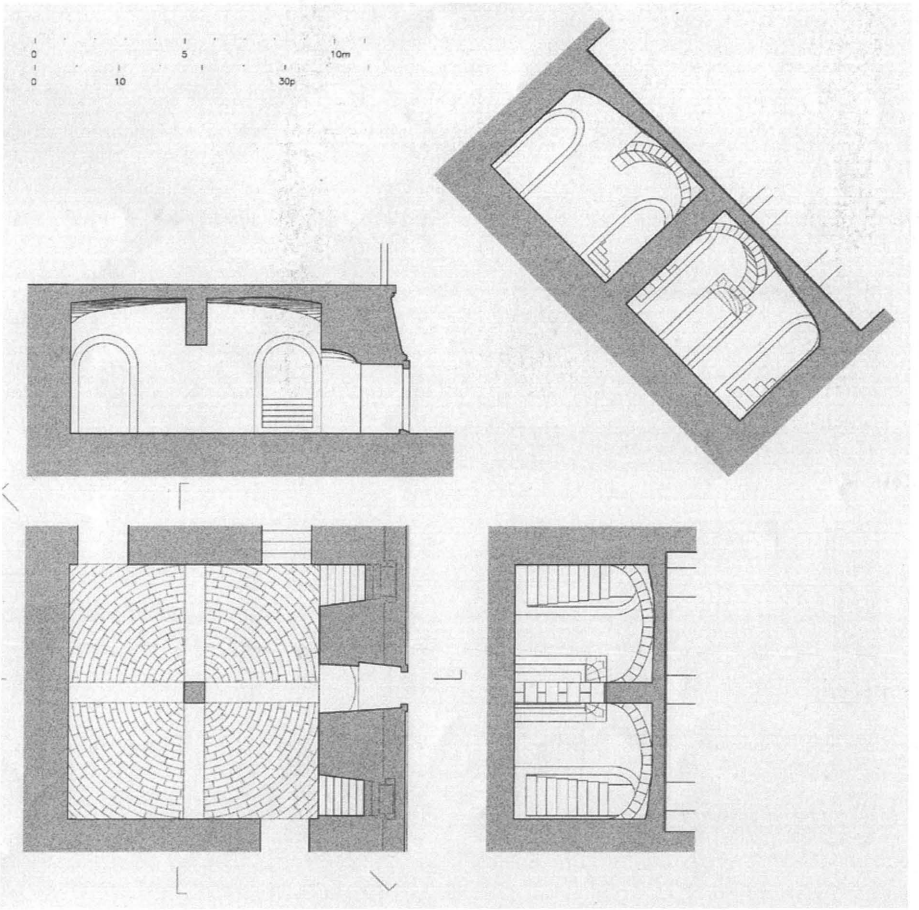


Figure 3
Plan and sections of the room under the discarded Noon Tower at the monastery in El Escorial

certain descent in the diagonal area of each course can be appreciated in all of the quadrants.

The conclusions of this work are summarised in a proposal of which could have been the original tracing of this vault (figure 4): it poses that the central column and the four arches were not in the initial plans. The important delay on the work of the king's private room, placed over our vault and the mistakes in the posing of one of the quadrants in which, in addition, there is filling in the unions with the supporting arches, could allow supposing that the area had to be redone. On the other hand, a column properly built would have been posed in the centre of the room; the solution with the arch loading over the entrance transom from the monk's garden is very strange; the descent in the central area would be difficult to occur in a vault laying on four central arches and, finally, if the construction would have been over column and arches from the beginning there would not be intermediate filling.

The geometry of the vault seems to have been born from its diagonal section, which revolving around a vertical axis generates the surface. The central planar area has been placed at the height of the highest point of the intrados and would comprise the eight central courses visible at present plus another two that are

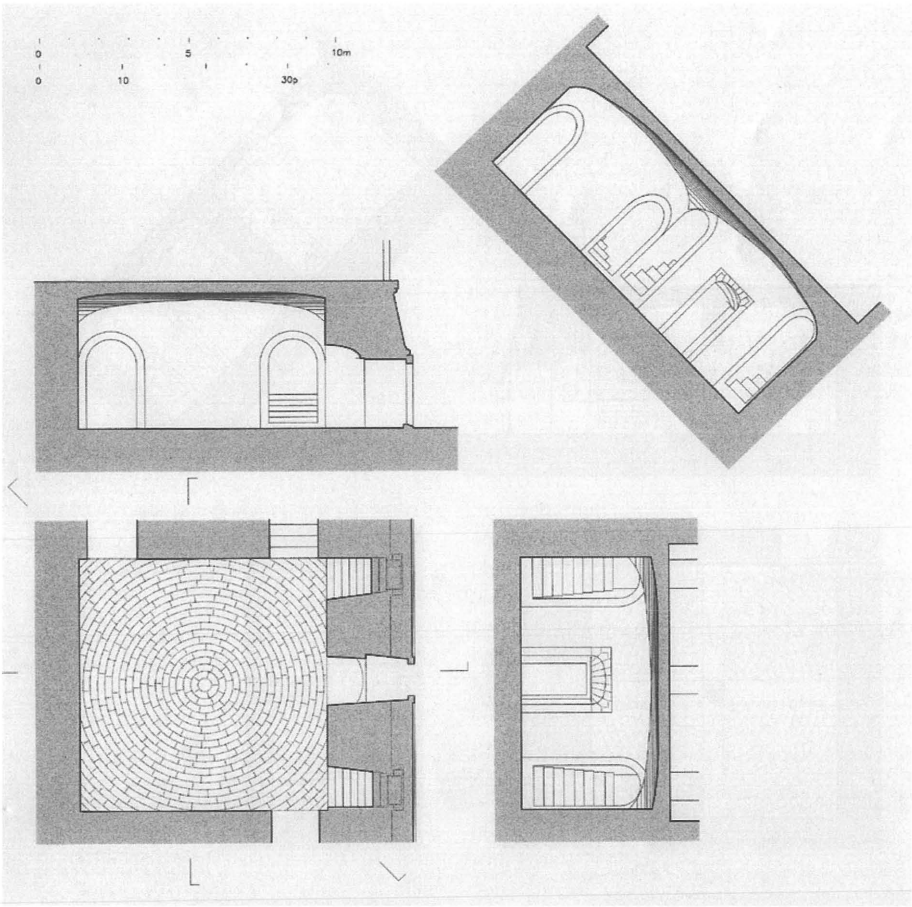


Figure 4
Hypotheses for the initial tracing of the planar vault under the discarded Noon Tower

supposed to be hidden behind the column, including the keystone. A smooth arch initiates the descent in an area of the vault in which the courses do not still reach the walls. The pendentive itself would have a diagonal section formed by a straight line, that would generate a revolving cone, and a final arch that would end the vault in the edges of the four corners of the room. Following this posing, the descent would be of around 7 cm in the centre, and would reach 10 in the thirteenth visible course at present. The laying surface of each course over the previous one could be solved with inverted conic beds, as if it were a transom arch revolving around its vertical axis (Rabasa, 2000, 216).

THE PLANAR VAULT UNDER THE CHOIR PLACE

Under the choir place in the monastery of El Escorial there is a unitary space, like the one of the large temple, following brilliant analysis by other authors (Sigüenza, 1602; Moleón, 1984; Ortega 1999). This paper analyses the set of all vaults, with a special stress on the famous central planar vault which was

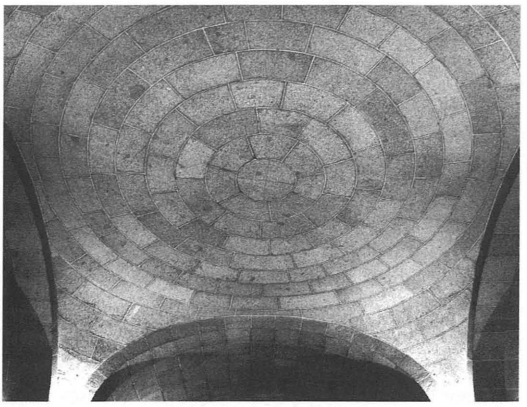


Figure 5
Planar vault under the choir place of the monastery in El Escorial

the second and final attempt to cover a space with a large horizontal stone surface at the monastery (figure 5).

At the end of 1565, the works of the church are divided into ten parties: five to the north of the longitudinal axis and five to the south (Bustamante, 1994, 412). The clerk of works Juan de Minjares is responsible for the whole works. That split tries to balance the work of all teams, each one headed by two stonemason masters. The space under the choir is distributed among four of the ten parties. Francisco del Río and Diego de Cisniega are in charge of one of them, comprising the south-western angle of the church: southern tower, half the façade and the arcade and a quarter of the space under the choir place. The rhythm of the works is not the same in all parties: on February 1581 the Congregation assigns to Cisniega the complete construction of the choir, including the space under the choir place reducing the parties of another three teams which were working in this area.[4] The works of the southern tower of the church go faster than those of its twin, what proves that Cisniega was very efficient. On December 1581, an expert valuation of the towers was done, being already finished by that date.

On March 1582, scaffolds are being made in the space under the choir,[5] in a very difficult area to this purpose, as it was the main entrance to the church work. On September 1582 an agreement for the construction of all the centring is reached with Juan Ramos.[6] On May 1583 the space under the choir was already finished as the measurement of the works is done on the 24th.[7]

The initial aim of this work was to analyse just the planar vault, but later it was decided to study all vaults in the space under the choir place and this unitary space was completely measured and drawn (figure 6). Herrera (1589, 13) describes the space under the choir place: «es quadrado, y tiene mesma forma que el Templo, y haze tres naves por cada lado de su quadro y sirve de cuerpo de la yglesia». The two main naves are covered by basket barrel vaults ; the planar vault with 28 feet span (7.81 m) covers what could be called the transept of this temple and four small sail vaults solve the corners. An intermediate arcade solves the transition between the space under the choir place and the church and we can find in there a transversal barrel vault and a false central sail one.

The five sail vaults we find in this area show an slightly enlarged plan in the direction of the

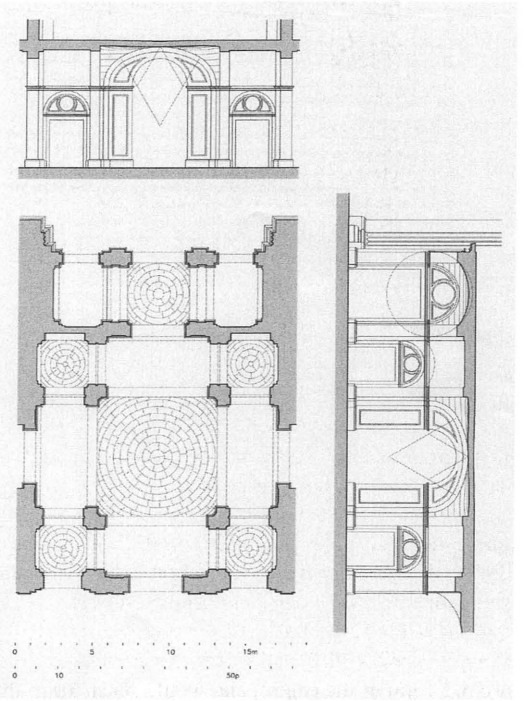


Figure 6
Plan and sections of the under choir place at the monastery in El Escorial

longitudinal axis of the church. The false sail vault mentioned above has an spherical casquete lowered almost 1 feet in height. The planar vault lays on four main arches which also conform the section of the main barrel vaults; those arches fit with enormous fidelity the traces described by Hernán Ruiz. The planar vault has been represented in the drawings of figure 6 in the deformed current state. The geometry of the quartering is perfect in plan, but not in height in which the descent looks very important in the central area and in the diagonals of the intermediate courses. The existence of a course with variable width is amazing: it is the first one laying on the main arches, thus, the highest among the pendentives.

Alonso de Vandelvira draws a vault which could have a lot to do with the one we are studying: it is the *square basket chapel with rounded courses* (figure 7). That vault could be cut by a horizontal plane at the height of the key stones of the main arches, generating a planar vault laid on four pendentives on basket arches but it would create a discontinuity at the start of the pendentives which does not exist at the piece in the space under the choir place. On the other hand, the vault by Vandelvira is a revolving surface: if the diagonal arch is a basket one, the main arches cannot be too and vice versa.

This work poses a hypotheses of initial trace for this planar vault. The solution that, probably, Herrera and Minjares designed, should response to a series of restraints : support on basket arches, diagonal section with smooth transition between planar area and pendentives and horizontal rounded courses. The configuration of the diagonal section becomes then the key point in this posing (figure 8). The central planar area would comprise the six central courses; in the last one, the highest point in the vault at present has been located, at a height of 8.034 m, almost 29 feet. At this height the planar area of the vault is placed. A three sections basket arch completes the diagonal section. The central area independent from the pendentives is drawn as in the planar vault by Juan Bautista de Toledo, initiating a smooth descent that would coincide with the first section of the mentioned basket arch. The vault in this area is

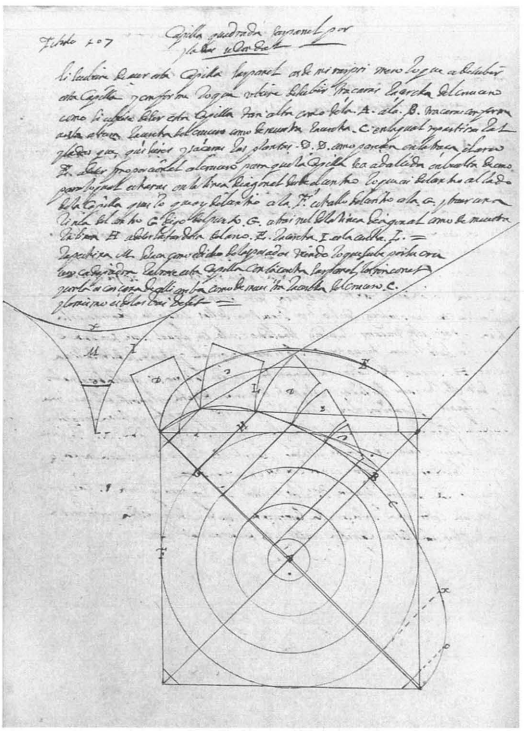


Figure 7
Square basket chapel with rounded courses, in Alonso de Vandelvira's treatise

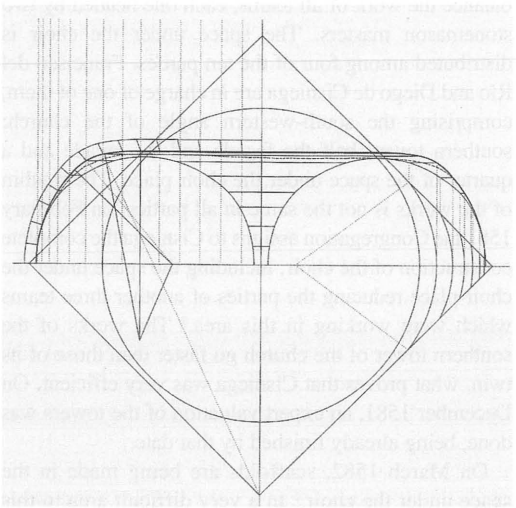


Figure 8
Hypotheses of the geometrical configuration for the diagonal section of the planar vault under the choir place

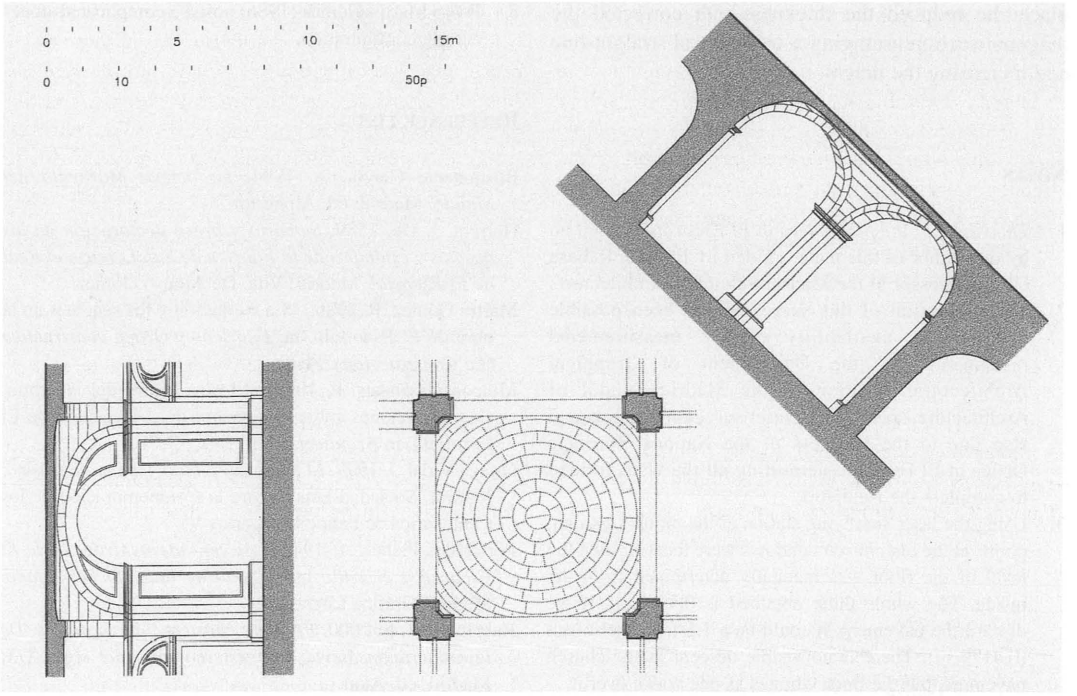


Figure 9
Hypotheses for the initial design of the planar vault under the choir place

formed by the revolving area generated by the corresponding part of the diagonal section; the joints between courses are then complete horizontal circumferences with center in the axis of the vault. In the pendentives, the courses are horizontal circumference arches, which lay on the diagonal section and on the two corresponding main arches and have then their center displaced with respect to the axis. For this reason, the transition course between pendentives and the central area presents a variable width. The surface of the voussoirs of this area is slightly warped and probably carved by approaching.

The current state of the diagonal section of the vault has been drawn with a discontinuous line in figure 8: the comparison between that state and the hypotheses for the initial trace allows a proposal of a descent in the keystone of 9.66 cm. On the other hand, the difference between the height of the choir floor where there is no deformation and the proposed intrados for the trace, gives a thickness for the vault of 28.1 cm. The laying beds of each course over the previous one could be conic, as in the planar vault by Juan Bautista de Toledo. In the case of the space under the choir place, the goodness of this posing would come confirmed by the recent construction of a plaster model of the vault with a scale of 1:10 by doctorate students of the School of Architecture of Madrid, leaded by Enrique Rabasa Díaz: the laying beds between courses are conic ones and the vault stands perfectly well.[8] Fray José de Sigüenza also describes this configuration (Sigüenza, 1602, 454).

The drawings in figure 9 describe the theoretical state of the vault before its deformation happened.

The relationship between the two vaults analysed in this paper is clear. The vault by Juan Bautista de Toledo has a longer span : 8.35 m × 8.63 m, versus 7.80 m in the one by Juan de Herrera. The thickness is almost double, the courses of a smaller width, and above all, a shorter height development. If that vault was a failed attempt as it is posed in this paper, Herrera, pupil of Toledo by that time, learned enough to build successfully the planar vault under the choir

place: he reduced the thickness and corrected the diagonal section arranging a sole central straight line and increasing the height.

Notes

1. *The vaults of the Monastery in El Escorial,* carried on by the author of this paper guided by Enrique Rabasa Díaz, professor at the Madrid School of Architecture.
2. The realization of this surveying has been possible due to the availability of the measurements instruments of the Department of Graphical Architectural Ideation of the Madrid School of Architecture, specially the laser surveying station, and also due to the kindness of the National Heritage Office at El Escorial, permitting all the visits needed to complete the fieldwork.
3. Using the laser surveying station at the monk's garden, points at the *old church* windows were located; then the level of the floor was manually determined from the inside. The whole thick obtained is 0.4682 m: if we discard the pavement, it could be a 1.5 feet thick vault (0.4179 m). There is no visible descent in the church pavement, but the floor vibrates as one walks over it.
4. Manuscript at the Monastery Library Archive, VII–41, transcript by Bustamante, 1994, 501 y 502.
5. Manuscript at the Monastery Library Archive, VIII–8, transcript by Bustamante, 1994, 506.
6. Manuscript at the Monastery Library Archive, VIII–3, transcript by Bustamante, 1994, 506.
7. Manuscript at the Monastery Library Archive, VIII–29, transcript by Bustamante, 1994, 508 y 509.
8. Pedro Martín Gómez (1986) posed a complicated stone-cutting configuration.

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Aesthetics, ethics and workmanship: The need for a cultural dimension to Construction History

Hentie Louw

Writing the history of a constructional event is, surely, as worthy an intellectual pursuit as any other. Moreover, since we are dealing with a human trait, we must assume that this activity, construction, and its objects are subject to value judgments, as explained in two of the traditional founts of philosophical discourse, aesthetics and ethics. It would not be possible to write its history otherwise, and the very fact of this congress taking place bears testimony to the *de facto* existence of such an identifiable field of study. Construction history has already been «named», i. e. particularized in the Hobbesian sense (Hobbes [1651] 1985, 102–3). The purpose of this meeting, as I understand it, is to take the subject into maturity: to seek a closer definition of concepts, of boundaries; to formulate guiding principles and foster the refinement of technique that would bring our work as construction historians wider recognition (academic, professional and public), thus «legitimizing» the activity and ensuring the future growth of the field of study.

As a group of scholars we are heterogeneous, coming as we do from a variety of related disciplines, reflecting the diverse nature of the subject matter. My own background is in architecture, so my view on these matters is inevitably coloured by this fact, and the first observation I would like to make from that perspective is that architectural history, although more securely established than construction history, also has gone through a process of re-examining its basic premises. It would appear as if most academic disciplines have seen intellectual turmoil of this kind in recent decades: having had to justify their very existence and having had their trusted objectives and longstanding practices challenged in the name of postmodern critical theory. It has happened to the core discipline, history, itself (Evans1997). It has happened to more specialized historical fields, for example the history of technology (Buchanan 1991; Staudenmaier 1994; Roland 1997).

While this may not always be a comfortable state for those caught up in the process, at least late-comers like us have the benefit of learning from the experience of others, since, in order to deal with the crisis practitioners in long-established disciplines have had to externalize the methodologies and philosophical premises by which they operate. Thus a wealth of historiographical knowledge was revealed which otherwise would have remained hidden, and a climate has been created that is susceptible to the introduction of new concepts potentially useful to the construction historian. In that sense it seems to be a good time to «open a new shop!'

The emergence of construction history as a subject in its own right can be seen as a belated manifestation of a trend —prevalent during the latter half of the 20th century— towards the progressive subdivision into specialisms of what had previously been thought of as an integrated body of historical knowledge. Most construction historians would probably agree that in terms of approach and content the new subject area falls somewhere between engineering —and

architectural history, with significant input from socio-economic history and archaeology. In Britain it appears to owe its existence as a separate field for academic enquiry to a feeling amongst some scholars that the role of construction in historic environments has not been given due recognition by historians, more specifically architectural historians, and therefore needed an independent voice, hence the formation of the Construction History Group (now Society), with its annual journal, *Construction History* (1985).

The roots of this tendency in architectural historical and theoretical writing, as well as in architectural practice, namely to separate out various constituents of the building process, privileging the artistic (as embodied in stylistic design) over all others, goes back to the Renaissance, but a crisis point was reached in the 19th century due to the impact of the industrial revolution. What for centuries has been a shared culture that linked those professionally engaged in the act of building then became permanently fragmented. On the one hand the parties involved were driven apart as never before, and set in competition by the centrifugal forces of industrial capitalism, on the other, they were caught up in the fractious stylistic battles of the Victorian art world. The ideological and operational framework for professional relationships within the building industry in Britain established at that time still prevails. It would, therefore, seem to be a good place to start searching for answers regarding the nature of a building culture, if such exists, that might form the epistemological basis for construction history as a field of intellectual enquiry. But first it is necessary to identify what exactly it is that we hope to find there.

At the beginning of this paper it was suggested that without scope for value judgment, or interpretation, as embodied in the philosophical categories of aesthetics and ethics, a subject cannot be classed as, «history», because these are qualities integral to all human activity, the *raison d'etre* for historical explanation. In other words, it is the «how» and «why» categories that are the critical criteria in this instance, not the «what, «where» and «when». In architectural history this point was well illustrated by Andor Gomme in his critique of the official survey of the Royal Office of Works in Britain, *The History of the King's Works»* (1963–82). Basically he concluded that this monumental work, for all its exemplary scholarship did not add up to a history, because:

> a history is more than a sequential chronicle – very much more than a congeries of parallel chronicles —or a narration, however faithful, of names and events important and trifling. It demands in the first place a sustained act of critical judgment, which in the greatest historians inerrantly discriminates between what is historically significant and what is merely incidental or trivial. In parts of the *King's Works* the lack of assimilation or consolidation of small–scale detail, the lack of critical selection and interpretation, leave the book lacking the essential qualities of history (Gomme 1986, 198).

It is a caution that we would do well to remember in our deliberations about the nature of construction history.

Three years earlier, in his inaugural address to the Chair in Architectural History at the University of London, Joe Mordaunt Crook, gave a useful summary of the characteristics that distinguishes architectural history from other types of history. He makes a plea for architectural history to act as a bridge between art, and technology, and social science, for it to function as an «agent of cohesion within the pantheon of history itself». Since all forms of history are concerned with the same thing, the explanation of the past, he argues that all that distinguish them from one another are, «the nature of the evidence with which they have to deal, and the techniques which have to be developed to assimilate that evidence». He identifies three different approaches to the subject:

> We can study that building as a monument, as a structure, as a tectonic equation, on internal evidence: that is the archaeological approach . . . Or we can study it vicariously, on the basis of external evidence, manuscripts, drawings, building accounts, correspondence: that is the documentary approach, . . . Or we can study it conceptually, as a work of art, as a design, in relation to aesthetic theory: that is the visual or art-historical approach . . . Architectural history, at its best, must encompass all three methods, because architecture is palpable history, culture in three dimensions. It cannot be created in *vacuo* (Crook [1983] 1984, 570–1).

Architectural history is, of course, only one of a number of disciplines whose territory overlaps with that claimed by the construction historian. Sorting out

what these subject boundaries are, and reaching a resolution as to how best to secure a separate identity for construction history without cutting its natural links with a range of other disciplines, is one of the tasks of this congress. I am assuming here that we are to continue along the disciplinary route initially embarked upon, for there is an alternative way: the interdisciplinary approach propagated by the so-called, «STS» movement, a group of, mainly American scholars who seek to treat Science, Technology and Social studies as one seamless entity (Cutcliffe 2000). Whatever the approach, in the final analysis it is the challenge of culture that has to be faced up to, if construction historians wish to be part of the wider community of historians.

The problem is that the notion of culture in itself is controversial; it is doubly so for the technological subject areas (Pacey, 1983, Pacey,1999). There are several schools of thought on what constitutes culture. *The Dictionary of Concepts in History* (Ritter 1986) identifies four basic definitions within two broad categories: an inclusive, society-oriented concept which derives from anthropology and is largely descriptive and neutral, and a more exclusive, normative one rooted in the humanities. Where construction history positions it self with respect to these two viewpoints will affect both its eventual character and its potential as an agent for change in today's building world. It is the last mentioned conception of culture that seems to pose the more intractable challenge to the construction industry, and by association the construction historian, and therefore perhaps is most urgently in need of clarification because of its topicality.[1]

An important reason for this complication with culture is the rather ambivalent stand taken traditionally by the building industry with respect to specific cultural values such as is represented, for example, in the question of standards, be they of an ethical or aesthetic nature, and those values stemming from «context-based insights» which bestow meaning, be they individual or socio-political in origin. The crux of the matter, as far as standards are concerned, seems to be the inescapable fact that the setting of and maintaining high standards of workmanship/ production incur additional demand on resources, and therefore inevitably work in opposition to a dominant driving force in the building trade in a market economy: the need for commercial viability.[2] As a consequence, issues regarding moral responsibility for «quality assurance» are habitually obfuscated —progressively so as mechanization, in Giedion's terminology, «takes command». The issues surrounding meaning are more complex and wide-ranging, but here too it is not difficult to see how, for example, a building industry, ideologically governed by what has been called, «technological determinism» —as was the case for much of the 20th century in industrialized countries— could, in refusing to accept the notion of subjectivity as a relevant factor in production, de-humanize the entire building process.[3]

The construction historian therefore has a dual task. Not only has he/she to create a framework for objective scholarship that could establish the factual basis for a rational understanding of the evolution of what is, essentially, a practical activity, he/she also has to create a framework for discussing different levels of subjective experience of that activity over time. The former falls well within the frame of reference for technical historical writing, and should be relatively straightforward to resolve. The latter, on the other hand, may require a new foundation upon which to build, especially in so far as the humanities are concerned. Architectural history is an obvious point of reference, but the architectural historian concentrates on the role of the architect, and tends to see the building world through the eyes of the «artistic» designer —a perspective that has become increasingly remote from that of the builder/craftsman since, during the industrial revolution, the Renaissance vision of a theory/practice split became widely accepted as the basis for the modern professional structure for the industry.

It is for this reason that I suggest it might be useful for us to retrace our steps to the 19th century, when the negative impact of the fragmentation and polarization of the construction process first assumed critical proportions in practice. It was then that the historic thread of seeing the «building act» as a continuum of human endeavour was finally broken leading, ultimately, to the Modern Movement's rejection of history itself as an irrelevance. Whereas the nature of this revolution, from an architectural perspective, has been comprehensively explored in all its ramifications, its impact on the building trades, other than in a material and political sense, has received comparatively little attention. We still view this world

largely through the glasses provided by the cultural reform movements of the Victorian era (or, in opposition to that).

It is difficult not to do so because it is so hard to fathom the exact role that craftsmanship played in building prior to the 20th century. Just because handwork is of such little consequence to the modern builder, we tend to forget how much the existence of a craft culture, governed by codes of what constituted «good workmanship», contributed to the creation of the historic built environment that we admire today. Construction history, I believe, will be flawed without a solid grasp on the part of the historian of the nature of this craft culture, founded on aesthetic and ethical codes no less real than those pursued in the fine arts, even though these were rarely articulated as such. It is our business to develop appropriate means that would facilitate this line of enquiry as well, and the 19th century, the moment when the tissues of this fabric were laid bare like never before in history, offers an ideal opportunity for studying a worldview that has become virtually extinct in Western societies.

What this might entail will be explored briefly by comparing the different responses of the building community to the advent of mechanization in the Victorian building industry. By looking at the history of the largest and most versatile of all building trades, the woodworkers I shall attempt to illustrate how mechanization worked its way through the building system in 19th century Britain and how, in the process, age-old conceptions of what craft is and stands for were fundamentally changed.

By the mid-19th century building, as an operational field in Britain had been systematized into three broad domains, each associated with a professional grouping. These were defined in 1869 by the architect, academic, and editor of the journal, *The Architect,* Thomas Roger Smith, as «the Art of Architecture, the Science of Engineering, and the Practice of Building» (Crook 1984, 560). The names of the categories are self-explanatory regarding the focus of its protagonists: to the first two, the architects and the engineers, were appropriated the functions of design and the direction of building projects, the last mentioned, the building craftsmen, increasingly under the hegemony of the master builder, carried responsibility for the physical construction process on site, for procuring materials and, initially, the manufacturing of all the specified building components. Up to the formation of their professional bodies (in 1818 and 1834, respectively), both the engineering and architectural «professions» recruited heavily from the ranks of the building craftsmen, and their educational as well as practice frameworks continued to reflect this kinship long after. In terms of its organizational structure, however, the new system was hierarchical and, while not always adhered to in practice, the polarized lines of demarcation nevertheless served as the benchmark for both social distinction and professional conduct. It also formed the basis for contractual arrangements throughout the industry. Two aspects of this arrangement in particular should be noted, as they set the parameters for operational behaviour within the industry:

— That the traditional creative/intellectual functions associated with building, and which carried most social status, had come to be reserved for the new class of professional, architects and engineers
— That only the activities of the building craftsmen, the lowest order in this pyramidic framework, were directly affected by mechanization.

Trades where the task consists of off-site manufacturing of relatively small items of a repetitive kind were obvious targets for the introduction of machinery in the workplace, and this applied to a significant section of the woodworking trade which was essentially workshop-based. Woodworking in Britain, England in particular, has a long and illustrious history and by the onset of the industrial revolution generations of practice had fine-tuned the trade into a complex, subtly graduated and inter-dependent network of skill-based activities, offering work opportunities to an unusually wide range of craftsmen. Comprising the arts of sawing, carpentry, joinery, cabinetmaking and carving, woodworking involved virtually every facet of building and furnishing, from the most mechanical of preparatory tasks to the most delicate of finishing touches. As a group, the woodworkers were amongst the best organized, best trained and best equipped of all the building and related trades; they were, as was pointed out before, also amongst the most vulnerable to large-scale mechanization. Consequently, in the space of a

mere three generations, from c.1815 to c.1895, a highly developed craft culture was destroyed as woodwork moved from being essentially handcrafted to being essentially machine-made. Exceptions to this were carpentry, whose role was equally balanced between the assembly of large-scale structural components and organisational duties, and woodcarving, which proved not to be commercially viable as mass production. A moving contemporary account of this struggle and the problems it caused whole communities of craftsmen is given by Henry Mayhew in his series of articles for the *Morning Chronicle* on the working conditions in London, 1849–50 (Mayhew 1850).

The plight of skilled craftsmen like the woodworkers in a rapidly industrialising British economy drew the support of cultural reformers like John Ruskin (1819–1900), and thus the building world got drawn into the struggle between two opposing forces that were shaping Victorian society: «aesthetic medievalism» and industrial capitalism.[4] Although few in the industry would entirely escape the consequences of this struggle, not all trades were equally conditioned by it. The professional class that was least affected by these events were the engineers who almost by definition belonged to the progressive industrial camp, driven by a quest for improvement through the rational application of science and technology. As long as they confined their activities to the «non-architectural» aspects of building —as was the case with a new class of engineer that rose to prominence at the time, the mechanical engineer— engineers were free to explore the opportunities offered by the expanding industrial economy.

Whereas the civil engineer, like the architect could never entirely escape the social context of construction, mechanical engineers concentrated all their energies on invention and manufacturing. In partnership with capitalist entrepreneurs they formed the vanguard of the campaign towards mechanization, and it is within this group that one is most likely to encounter what a former president of the Newcomen Society, S. B. Hamilton, denounced as, «the adult infantilism of go-getters», who, «used the industrial revolution in the nineteenth century only as an opportunity to exploit the new means of power and production for immediate personal gain, heedless of the human and material waste and mess that they were leaving to be cleared up by posterity» (Hamilton 1945/6, 7). It was this class of men, the precursors of the modern industrial engineer, or engineer-managers who was responsible for developing the technology for mechanized woodworking. (Louw 1992, Louw 1993, Louw 1995, Louw 1996).[5]

The architects, by contrast, found themselves, almost inadvertently, in the thick of the battle and remained ambivalent towards its objectives, which eventually caused the architectural profession, under the pressure of the competitive industrial environment, to split along art v. business lines. (Curiously, this latter development seems to have followed an aesthetic agenda, with the classicists, who saw themselves as «rationalists», generally being more willing to compromise and engage with technological experiment than the Gothic Revivalists who, with few exceptions, carried the flag for «free», artistic expression in a handicraft tradition, modeled on an idealized medieval society). Part of the problem lay with the general sense of insecurity on the part of the architects who found their bid for higher social status and leadership within a transforming building industry undermined in a number of ways:

- By the increasing scale, complexity and cost of building operations, which required new contractual arrangements and stricter financial control, and brought a new specialist, the quantity surveyor, into the architect's traditional domain.
- By the new structural techniques, materials and services that put the architect in direct competition (often to his detriment) with the other new design professional on the scene, the engineer, for on-site supervision and control of building operations.
- By the rise of the general contractor, employing several trades «in-house» on building projects that progressively cut the architect off from direct dealings with master craftsmen on site.
- By the perfection of mechanized processes for the mass-production of architectural ornament, which encouraged the proliferation of wholesale furnishing firms providing comprehensive interior decoration services for architectural projects, independent of the architect.

Design was the traditional skill of the architect least compromised by the industrial revolution, even

though their inability to create a modern style equal to those of historic cultures which they admired and copied, were calling into question their claim at being artists on par with the painters and sculptors. Not only did their design methods in the process become more abstract and paper-based, the architects also became progressively more protective about the design skill being their «trump card» and exclusive professional right. Unfortunately, this trend coincided with the demand for a greater participation of artisans, including building craftsmen, in the creative process when it became clear that the decorative arts could make a significant contribution to the national economy, which was under threat from international competition in the production and trade of manufactured products. Craftsmen too were now called upon by society to make a specific contribution by improving their skills and expanding their creative capacity. The ensuing campaign to achieve this transformation of the artisan into the so-called, «art-workman» at first concentrated on education: a government-sponsored programme of establishing design schools throughout the country (Bell 1963), and private initiatives such as the Architectural Museum project promoted by the «Gothicists» within the architectural profession (Louw 1996, 23–25). Both projects, for reasons that will be discussed later, failed to achieve the desired results.

Parallel to these attempts at reform, from c.1850 onwards grew a more radical, anti-machine, anti-professional campaign, which we now know as the Arts & Crafts Movement. Inspired by the teachings of Ruskin and William Morris (1834–96), and repelled by the crassness of mass-produced furnishings, a group of young architects set out to create an alternative model for building and furnishing practice to the prevailing, mechanized industrial one. They were highly critical of the architectural establishment as well as the industry and sought to base their practice instead on the collaborative medieval guild structure, in which the design and making processes were to be re-united by a brotherhood of art-workmen: architects and craftsmen operating on an equal basis in communal workshops, striving together towards achieving holistic projects serving socialist objectives. Ultimately, the quest for an «earthly paradise» by Morris and his fellow art workmen too foundered on the commercial realities of late-Victorian Britain, but not before they had established the norms against which subsequent notions of craft are measured.[6]

Thus caught, between the relentless push of the manufacturers towards full mechanization of the industry on the one hand, and the equally strong pull of the cultural reformers towards the recreation of pre-industrial world, on the other, how did skilled craftsmen respond to these challenges? What aesthetic and ethical positions did they take, and how did these compare with those of other building professionals? Because more was written about the British working classes and their conditions than they themselves articulated, it is a very difficult theme to study with confidence. Nevertheless, enough first-hand testimony survives in diaries, evidence to official enquiries, exhibition reports, newspaper surveys, trade-union literature and professional magazines and handbooks, to allow some conclusions to be drawn. In the following section I outline a scenario for this event, based on my own research into the case-history of the woodworking trades during the 19th century (Louw 1992, Louw 1993, Louw 1995, Louw 1996):

Machinery: Regarding the «machinery question», the catalyst for industrial progress, the woodworkers generally seem to have held a pragmatic view point, responding to its challenge in direct relation to the extent of the perceived threat to their livelihood, not on ideological grounds. Carpenters and joiners participated in the making of machines throughout the century and protests against the use of machinery, though they did occur, were neither common nor exclusively focused on machinery. The craftsmen were aware of the machine's potential for lightening the burden of physical labour, for expanding the scope of their jobs and for creating extra work. They were, however, not blind to its potential for making their skills redundant and their positive attitude changed as soon as the pace of industrialization accelerated, and the full implications of the division of labour principle that underpinned mechanization became clear during the 1850s. Up till then the skilled workers seem to have been confident of their ability to compete with machinery, if not in terms of quantity at least in quality.

Morale: Their spirit was broken by the ruthless exploitation of their labour through new systems of

workshop management and the progressive efficiency of woodworking technology. In an increasingly politicized atmosphere the woodworkers played a leading role in the formation of the labour movement, fighting not only for better wages and working conditions, but also for more direct benefits to the worker from the application of machinery in the workplace. American influence led to the production of a smaller, cheaper class of woodworking machine suitable for general use in the building industry and this had a significant impact. The final blow to the skilled woodworker as a force in the British building industry came during the so-called «Great Depression» (1873–1896), with the large-scale importation of ready-made woodwork from abroad. This stimulated the local industry to mechanize to an even greater extent, demoralized the craftsmen even more and removed any prospect of a general return to handwork practices within the trade. By the early 20th century the culture that sustained their once peerless skill-base had largely disappeared.

Skill: For most of the 19th century superior hand-skill remained the benchmark for quality amongst the building trades and the key to success and status within a conservative industry organized on strict hierarchical lines. Amongst the woodworkers joiners and cabinetmakers were seen as the ones possessing the highest levels of skill, with the best training and most expensive sets of tools, of which they were inordinately proud. Master craftsmen like these usually operated independently and had considerable autonomy in the workplace. They were amongst the best in the field and natural candidates for a new class that emerged towards the middle of the century, the so-called, «labour aristocracy». Commercialized mechanization based on the division of labour principle undermined the foundations upon which the skilled woodworkers' identity and status rested by rendering their hard-won facility for handicraft uncompetitive and ultimately redundant. The need to earn a living drove many to what was called, «scamping», i. e. the lowering of standards of workmanship in order to achieve a higher production rate, causing a moral dilemma with a distinction being drawn in the trade between «honourable» and «dishonourable» practice. The progressive integration of machinery in working practices even began to blur the definitions of what constituted machine-work and what handwork and it is clear that, as far as high quality work is concerned, by the 1870s the two modes of operation were beginning to achieve parity in the eyes of the workmen. Simultaneously, the concepts became politicized again with «machine-work» in its derogatory sense being associated with sub-standard work, unemployment and eventually all imported joinery products.

Split: The emergent trades' union movement, the self-proclaimed champion for workers' rights, paid little attention to the decline of skill and standards of workmanship in the specialist trades. It was the Carpenters' and Joiners' Companies, the modern successors of the traditional crafts guilds, who joined forces with the reform movement in architecture in order to defend the cause of the skilled workers by promoting the conservation of a craft culture and its concomitant educational systems. This allegiance caused a split within the ranks of the woodworkers — which resembled that which occurred within the architectural profession quite closely— between the «artists» or «Gothic men», and the «tradesmen» or «operatives». The term «Gothic men» indicates that the craftsmen involved were drawn from the top range of skill and working mainly in the Gothic idiom. The consequence of this development was that the bulk of the skilled workforce became cut off from this cultural movement with a complete breakdown of communication between the various groups concerned.

Reform: For their part the reformers seem to have been either unaware of, or insensitive to the difficult conditions under which craftsmen had to operate, expecting them to unlearn and reform well-honed physical skills and devote what little free time they got in a tough working environment to a programme of cultural self-improvement, for which the facilities were mostly inadequate and inappropriate. That goes for the government design schools as much as for the Architectural Museum project. The Arts & Crafts Movement at least recognized this fact and sought to develop a more congenial work environment and better training facilities, but their efforts, like those of the other reformers were hampered by an inability within their group to accommodate a taste-culture which differed from their own, essentially partisan one. It mattered little whether the motives behind this were social or aesthetic, or both, the outcome was the same

and herein lay one of the most intractable conundrums of this whole issue. In the final analysis, there seems to have been no real place for the ordinary skilled workman in the idealized world of the architectural reformers, not unless they changed their nature, their tastes, their skills and working practices. This most of the craftsmen either could or would not do.

Horizons: From the perspective of the craftsmen we get a different picture. Brought up within a skill-based craft culture that went back for centuries, their horizon was circumscribed by custom, tempered (but only incrementally so) by opportunity and natural talent. As individuals they were free to select a career within a general trade, in this case focused on the working of wood and, according to their interests and abilities, train to do a particular kind of work. For those with a desire to engage with structural and organizational tasks, carpentry was an obvious choice; for those who liked indoor work, demanding a high degree of manipulative skill, joinery and cabinet-making served, while those with a more artistic bend could take up wood carving.

Re-orientation: Ever since the guild structure in Britain finally began to collapse in the 18th century, the more ambitious amongst working men had opted to pursue careers in the emergent building professions, but the old craft tradition with its finely calibrated scale of manual activities still held sway as the operational framework for most building workers in the early 19th century. Due largely to the efforts of one individual, Peter Nicholson (1765–1844), cabinet-maker-cum-architect-cum-mathematician-cum-author, the woodworking trades had been given a rational science-based theoretical foundation. This re-alignment of the craft of woodworking towards science was reinforced later in the century by the government-sponsored programme of technical education. There was a natural affinity of this science-based technology propagated by Nicholson and his followers with the sober, rule-based rationality of the classical style of architecture —a language which, after two centuries of continuous practical application the English craftsmen had made their own, regarding technique as well as taste.

Culture Clash: However much the working men may have admired cultural reformers like Ruskin and Morris —and there is ample evidence of that being the case— the Gothic Revivalists' demand for the craftsmen to abandon the security of a well-understood decorative language, for which a sophisticated technology had been developed, in order to work with what they considered to be primitive tools according to the whims of designers who themselves were in the process of learning the grammar of the new idiom, was neither realistic nor fair. Moreover, serious-minded craftsmen were totally bemused by the fickleness of stylistic fashions capable of executing a complete volte-face from one generation to the next, without any logical explanation or defense. A classic example of this is the artistic community's attitude to the question of the relative aesthetic quality of hand-made v. machine-made goods. In the mid-19th century, when machined wooden products were rough compared with the highly finished hand-made item, the «smoothness» of the latter was valued most. When, later in the century the advanced machine technology could produce goods superior in terms of finish to those made by craftsmen, it was the roughness of surface, or «texture», that became the ideal.

Two Paths: Master craftsmen in the woodworking trades in Britain seem to have valued sound construction, economy of execution and precision of workmanship above artistic flair, which is why they failed to be impressed by the much lauded work of French joiners and cabinet makers, even when confronted by these products at international exhibitions and during visits to that country. Given the over-arching context of the divisionary social class structure of Victorian Britain within which these developments took place there was clearly little prospect of reconciling such contrasting perspectives, and thus of bridging the ever-widening gap developing between the arts and technology within the building industry throughout the 19th century. It is a legacy that is still with us today.

The point that I have tried to make in this paper is that, instead of a humanities-based notion of culture being peripheral to the construction historian —a view some practitioners in the field may well subscribe to— it has the potential for acting as a leaven to raise the standards of debate in our subject area, as well as for allowing access to parts of the

inner workings of the field that we seek to explain which no other line of enquiry permits. Without this critical presence within his/her reference-base, or, academic «toolkit», the construction historian's grasp of the constructive act as a meaningful human activity will definitely be the poorer, and so would be his/her contribution to the future well being of this activity.

I have gone further to suggest that in order to understand the nature of construction history as a subject, and its potential for becoming a new discipline, we have to know what happened to building during the industrial revolution. Why? As I have tried to show with the brief description of how mechanization affected the craft of woodwork during the 19th century, something fundamentally changed within the fabric of the industry at that time which caused a general breakdown of communication between the spheres of art and technology —the loss of a common language, rooted in a common value system. Woodworking in the early-20th century was different from woodworking in the early-19th century in a fundamental way. Hannah Arendt, in her book, *The Human Condition*, has identified what may lie at the heart of this transformation that nearly every craft process in society underwent: She argues that during the industrial revolution usefulness achieved through good workmanship, the ideal of *homo faber,* man the maker, the «fabricator of the world», have been sacrificed to abundance, the ideal of *animal laborans*, man the labouring animal, the consumer. Craft was replaced with labour, that «leaves nothing behind . . . the result of its effort is almost as quickly consumed as the effort is spent' (Arendt [1958] 1989). Construction historians, wishing to deal with the full span of building history, including both the pre-industrial and industrial eras, therefore finds themselves confronted with a dualistic entity. Either a pluralist stance is adopted with the acceptance that our «specialism» cannot achieve disciplinary status, as Malcolm Dunkeld has concluded some years ago (Dunkeld 1987); or, we continue to search for that elusive common thread in building that would provide the focus needed for completing this task.

Should the latter route be taken, there seem to be two different approaches to be explored: one is centred on the on the process of building as the generating force; the other takes the object of building as the guiding principle. Tom Peters has made a strong case for the former (Peters 1996), and this would undoubtedly be an attractive proposition to a large proportion of those currently working in the field. The second option links up with traditional art/architectural history and, therefore, may be unfashionable. However, I do believe that it ought to be given serious consideration as well. In which case, an obvious touchstone would be the notion of «craft» or «workmanship», as defined by David Pye: «the application of technique to making, by the exercise of care, judgment and dexterity» (Pye [1968] 1995, 118). After having been written off as an obsolete concept by industrialists for nearly a century now, the ideal of a craft culture as a humanizing force in the building industry has not gone away. In fact, it seems to be sprouting again and has gained some rather unexpected allies, even in the futuristic world of electronic media (McCullough [1996] 1998). At a time of growing concern about the future of biological life on earth (Wilson 2002) it is important to remember that human skill too is a precious natural resource, and the field of construction has in the past nurtured some of the finest specimens of this human attribute. As construction historians we are the custodians of the memory of that achievement. Perhaps the most effective way of keeping that memory alive would be to study the connections between the craft of yesterday and the craft of today; to reveal what bonds of kinship there might lie under the apparently dissimilar features of the old and the new.

For the essence of a craft culture does not reside primarily in the physical reality of the artefact; it rests in the value systems that condition the creation of that artefact. The name by which this enveloping entity has traditionally been known is, «workmanship». The scientist-philosopher, A. N. Whitehead, has given us another, more forward-looking version of this concept which could guide such investigations. In an essay entitled, «The Aims of Education», he calls this quality, «a sense for style':

> It is an aesthetic sense, based on admiration for the direct attainment of a foreseen end, simply and without waste. Style in art, style in literature, style in science, style in logic, style in practical execution have fundamentally the same aesthetic qualities, namely, attainment and restraint . . . Style in its finest sense, is the last acquirement of the educated mind; it is also the most useful. It pervades the whole being. The administrator with a sense for style hates waste; the engineer with a sense for style economises his material; the artisan with a sense for style prefers good work. Style is the ultimate morality of mind' (Whitehead 1932, 19).

Notes

1. As evidence, both of a fault line in cultural relations across the building community in Britain, as well as its nature, we need look no further than the furore caused recently by the English architect, Richard MacCormac's criticism of the lack of cultural reference in the construction industry's affairs (MacCormac 2002).
2. The most effective critic of the negative nature of the «competitive system» propagated by industrial capitalism remains the American economist, Thorstein Veblen (Veblen 1914).
3. I am referring here to the reality in practice. Conceptually, as Tom Peters (Peters 1996, 351–6) has shown, the building process contains a dynamic aesthetic of its own that resonates with a larger cultural as well as natural context.
4. The best, if perhaps unnecessarily pessimistic, overview of this struggle is by Martin Wiener (Wiener [1981] 1985).
5. Again, I am referring to the realities of 19th century industrial practice, and the ruthlessness of the pioneers who laid the foundations of the modern integrated system of human labour and machinery, which Lindy Gibbs describes in her book, *The Rational Factory* (Biggs 1996).
6. The best «behind the scenes» book amongst the extensive literature on the Arts & Crafts Movement is by Peter Stansky (Stansky 1985).

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The Colosseum: Quality and efficiency of construction

Giovanni Manieri Elia

The aim of this paper is to analyse certain specific aspects of the construction, structure and building site of one of the world's most studied monuments —perhaps the most studied— referring back to the ample extant biography for more general information. With this goal the study proceeded beginning from a thorough direct analysis of the monument and returning nevertheless to observe directly details already pointed out by various authors.[1]

The criterion for the interpretation of constructional and structural questions has been to rexamine the choices made by the ancient builders within the context of their way of reasoning and their method of organising the production process with well-defined objectives in mind, taking into consideration also the means at their disposal.

The duration of the construction works of the monument remains uncertain: according to some authors, the building works took about ten years, with a further two years for finishing-off;[2] according to others, the works were completed much sooner.[3] What is certain is that the period of execution was extraordinarily short and at the moment of the inauguration of the Colosseum, which took place in 80 AD, the construction was not yet completed in its current form, since almost certainly the attic and the greater part of the structure of the hypogea under the arena had still to be realised.

As noted many times, there are several indications that suggest that the construction work of the whole amphitheatre was a complicated operation, which was conceived, planned and carried out under constant and careful control in order to maintain a high level of productivity during the entire period of the building works, therefore taking into consideration always those aspects connected to efficiency —which was understood not only as speed of execution but also as qualitative productivity— as well as the structural solidity *(firmitas)* and long life expectancy of the building with the least expense possible.

From this point of view, we need to evaluate all those choices that were made during the period of construction to allow work to *proceed contemporaneously on many fronts* and in different places. The main problem in fact was represented by the logistical and organisational challenge posed by the need to have many hundreds of people work in the same place. As a matter of fact, the low level of mechanisation in those days entailed using a workforce that had a very high content of «slave labour». Since this sort of workforce was practically unlimited and low in cost, and given that there were no problems concerning the supply of materials that were easily available in the areas around Rome, the question of the *multiplication of the working spaces* of the building site was of primary importance, from which arose the necessity to distribute the works that were being carried out contemporaneously in different places.

Firstly, the blocks of travertine, but also those of tufa, arrived on the building site already squared, by way of the wide roads specially laid out to allow the

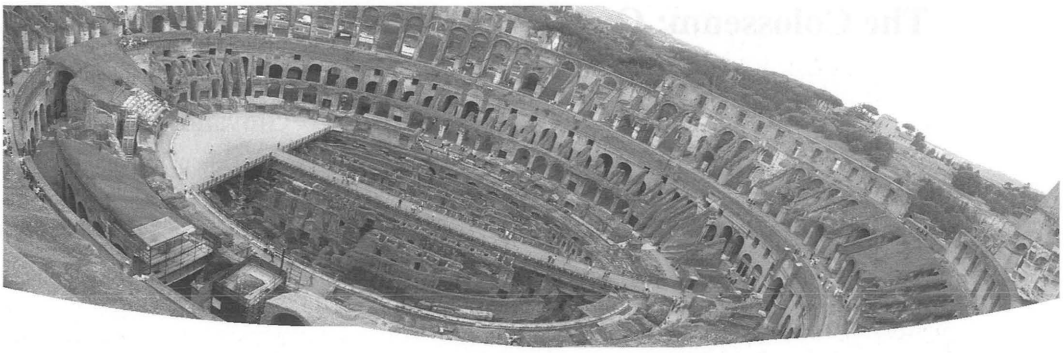


Figure 1
Wide angle panoramic view of the interior of the Flavian Amphitheatre in its current state

simultaneous transit of a large number of carts. Once the squared stones arrived on site, they were grouped according to their height in order that they could be laid in the same horizontal row. In fact the various stone courses do not have the same height in order to minimise the work of dressing the stones, making the blocks uniform and finishing-off.[4] A large volume of the work was therefore carried out off site, probably at the quarries where the material was extracted, cut and made regular. At the same time other large blocks of marble were in production with the sculptors for the execution of that great number of statues, which, once the structure was completed, would have been placed in every external arch.

The dimensions of the impressive scaffolding, of which traces remain in the points of support, also seem to indicate the necessity of being able to reach high positions with substantial loads —presumably consisting of men and heavy materials— before the conclusion or rather before the final structural solidity of the intermediate levels had been reached, with the evident intention, therefore, of working contemporaneously on several levels. There are those who carry this concept forward so far as to maintain that the «piers» in travertine, which are visible enclosed within the radial walls built in tufa or brick, were raised before the walling that contains them, in order to be able to build a ceiling in concrete above the piers as soon as possible, so as to allow several teams of workers to work contemporaneously on several levels.[5] In reality, certain constructional details, such as the scarcity of toothing between the load-bearing arches and the above-mentioned piers, combined with considerations regarding the execution of the work such as the difficulty of constructing a wall with large blocks of tufa that would have to be placed between pre-existent piers and with a ceiling above, which would have complicated greatly the lifting systems, make one tend rather towards the interpretation according to which these vertical elements in travertine, that pass through the walls in all their height, are intended to have the greater loads concentrated upon them, collecting together the forces of compression along predetermined preferential vertical alignments (Lugli, 1957, pp. 331–332; Giuffrè 1988, p. 126). (Fig. 2) Indeed, from a mechanical-structural point of view it is obvious that the loads concentrate on the most rigid structure constituted precisely by the piers in travertine, compared with the parts adjacent to this structure, which, relatively, are more compressible.

Other elements that relate to the rationalization of the building site and therefore to the speed of execution, consist in the widespread use of modular elements in a building that in line with its oval form is anyway geometrically regular, repetitive and with few exceptions. All the steps of the stairs, for example, had the same measurements, as did the marble seats for the spectators which all had the same dimension of 57 centimetres each.[6]

The entire amphitheatre was then divided into sectors, each of which was entrusted to a different contractor. Every building firm, responsible for a sector, worked with his own workmen and could take



Figure 2
The structures in travertine were those most burdened by the loads, as confirmed by the presence of vertical cracks caused by crushing throughout the height of this pier, placed on the side towards the Celio

advantage of a certain freedom of choice as regards technical solutions in the execution of the building; as proof of this, there exist in different places within the building notably different building techniques in parts which are architectonically the same, which, rather than second thoughts in the course of work, seem to be dictated by different and competing standpoints as regards the execution of the building.

One example is represented by the corbels present in the piers of the third tier of the external circle, which would have served to support the wooden structure of the scaffolding. (Fig. 3) In one sector of this circle (towards the Colle Oppio), the corbels are placed carefully at the same height, so much so that some have been chiselled painstakingly along their upper edge to remove a few centimetres in order to recover the established height for the support. (Figs. 4 and 5) Such an arrangement would lead one to



Figure 3
The corbels present on the internal face of the piers of the third tier would have been used to support the wooden structures of the scaffolding

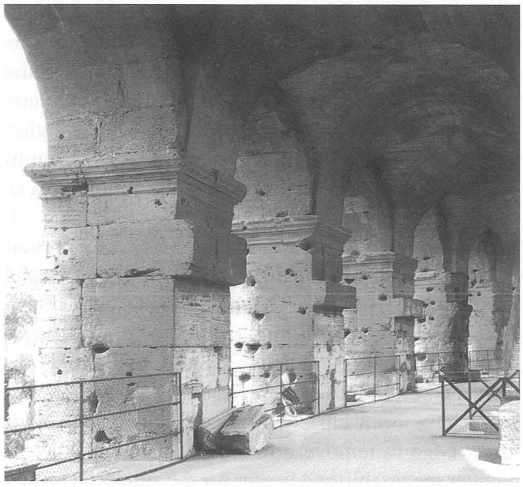


Figure 4
In some parts of the building (towards the Colle Oppio), the corbels are carefully placed at the same height

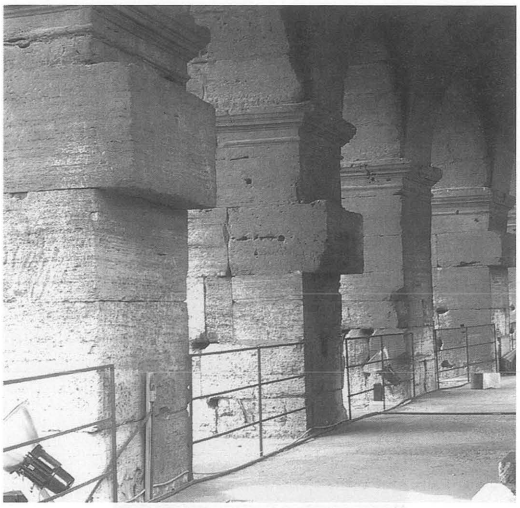


Figure 6
In other parts (towards the Fora), the corbels are placed at apparently random heights, or otherwise they are missing altogether



Figure 5
This block has been carefully chiselled by some centimetres along its top edge in order to recover the established height for the corbel

assume the positioning of a horizontal beam between them. In other sectors (towards the Fori Imperiali), however, the projecting blocks are placed in an apparently casual manner, or, in some cases, lacking altogether. (Fig. 6) The difference in height could be explained by the presence of oblique struts set in position on top of these (Cozzo, 1971, 46, fig. 28). The choice not to build the scaffolding directly on top of the roofing of the second level, thereby discharging the weight onto the piers below of the second circle, and instead to support the scaffolding on brackets projecting from the wall, allowed the builders to leave the floor completely free and therefore to build on top of this, without any obstruction, the structures of the second ambulatory of the third tier. (Fig. 7)

The junctions in which the parts realised by the workshops of different sectors meet are still clearly visible; it is precisely here that constructional inconsistencies, such as errors in the scansion of the architectural measure or in defining the height of the impost of the arches (Fig. 8), give rise to faults in the correspondence between the sectors which stand out in a very obvious manner. Examination of the structure in its current state reveals even quite notable irregularities but evidently, given the impressiveness of the whole, they do not disturb the original general architectonic effect. On the other hand, the correction of constructional incongruities of this type during the course of the works would have involved the remaking of substantial parts at a high cost, both in economic terms and in the time required for

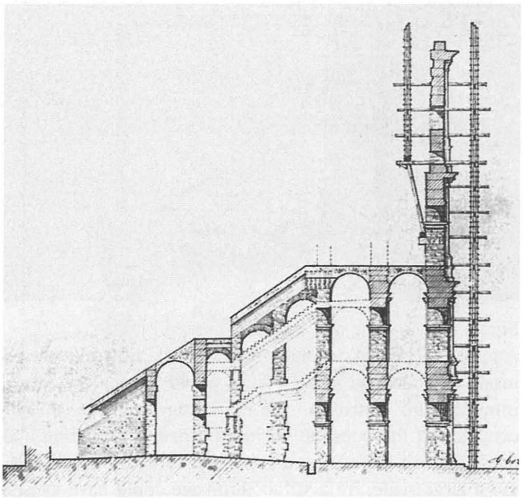


Figure 7
This diagram illustrates the theory advanced by Giuseppe Cozzo (1923) regarding the configuration of the internal wooden scaffolding supported on the corbels projecting from the wall. This solution enabled ample space to be left free on the second storey, thereby facilitating the work of the builders

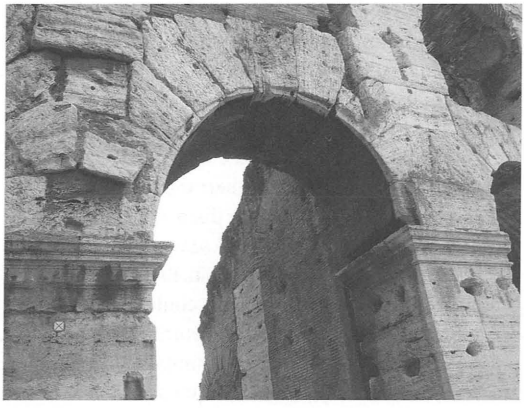


Figure 8
The irregularities in the architectural measure mark out the points at which the sections executed by the different building firms meet

execution. Also, the lack of a perfect vertical alignment between the piers of the superimposed orders in the façade, verified by surveys, demonstrates the determination to *sacrifice exactitude in execution to the productive efficiency* connected to the autonomy of the individual building teams (Conforto and Rea 1993, 73).

From analysis of the constructional details of the entire building there seems to emerge a *general rule* to which the workmen had to conform: to *take care in the details only in the event that it proved inevitable.* Attention to detail, in fact, represented a cost, both in terms of economics and time, which increased enormously with the refinement of the execution of a building, that is, with the reduction of the approximations and tolerances that in fact are evident in the structure of the Colosseum. To employ resources for unnecessary refinements entailed a loss of efficiency, strictly to be avoided. There are many examples of the application of this rule in the finishing-off, but its application is also evident in structural elements. For example, there are some piers (Fig. 9) in which the vertical joints of the superimposed courses

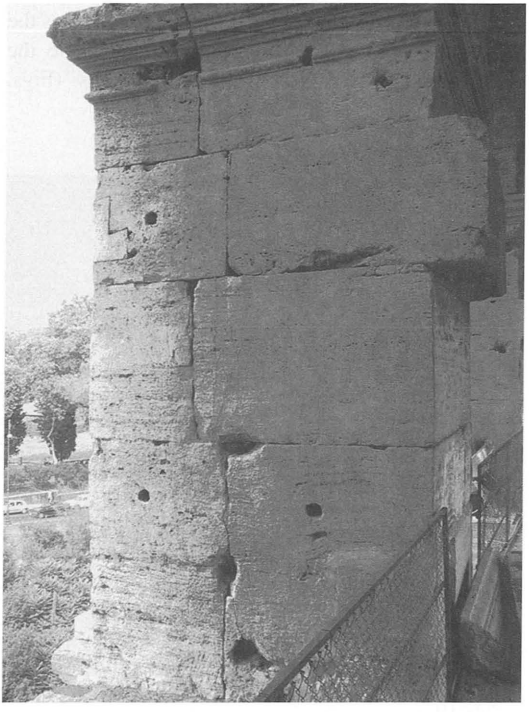


Figure 9
This travertine pier highlights the fact that just a slight staggering of the vertical joints between the external and internal blocks was considered sufficient

are staggered only very slightly. Evidently the Roman builders did not consider a substantial staggering of the joints essential, and the stability demonstrated by the age-old structure has proved them right. On the other hand, there were no exceptions to the painstaking care given to other details that were considered important. Analysing, for example, the attitude of the geological strata of the travertine, these are always parallel to one of the two side faces of the voussoirs (Giuffrè, 1988, 131, figs. 63–64). This manner of placing the stone was considered irremissible, clearly in relation to the Roman builders' knowledge that travertine was a material which was not at all isotropic.

As for the barrel vaults and groin vaults of the monument, as is the custom of the Romans, they are carried out with the use of *opus caementicium,* bedded down in horizontal layers on a wooden centring. A building technique that appears for the first time in the Colosseum (Rivoira, 1921, 116, figs. 98–99), which is still insufficiently studied but certainly to be evaluated from the viewpoint of a greater speed of execution and static efficiency, is the insertion of interconnected brick arches inside the *opus caementicium* forming the barrel vaults. (Figs. 10 and 11)



Figure 10
The presence of «ribs» inside the concrete of the barrel vaults, formed by brick arches interconnected by bipedal bricks, suggests that these too have their functional origin in the necessity of reducing the centring



Figure 11
Another theory to account for the brick ribwork, placed inside the concrete barrel vaults, could be that they were intended to distribute the shrinkage of the mortar constituting the concrete during the period of setting and hardening, in this way rendering the shrinkage negligible. On a large scale, in fact, the shrinkage could have caused dangerous cracking

There are various hypotheses regarding the function of these ribs: according to some, they would have served to make the structure more rigid, according to others to divide the mass of fresh concrete into sections; but the most credible theory is that this ribbing had the function of relieving the wooden centring and the props below, which consequently could be much more contained in size, since they had to support only little more than the weight of the ribbing and not all the weight of the mass of fresh concrete. Furthermore, the use of the ribs allowed the centring to be dismantled much more quickly. This constituted a saving in materials because as well as a reduction in the dimensions of the props, the fact that the props could be dismantled sooner also allowed the same centring to be reused several times; props that were simpler and slimmer were also more quickly and easily manageable. Moreover, and this seems to have been the most important thing, the sooner that a vault cast only a short time previously could be made functional, the more time was saved.

There is another measure, however, that with every probability was put to the test with the aim of simplifying the carpentry work, and this was the technique that anticipated the execution of a groove cut into the face of the travertine arches that were adjacent to the groin vaults in *opus caementicium.* On

the inside face of the travertine arches on the third tier of the external circle, there is in fact a furrow or groove cut into the stone at a regular distance from the intrados or lower curve of the arch (Figs. 12, 13). According to an early interpretation, this operation would have been carried out to aid the adhesion between the concrete of the groin vault and the wall of the arch. It is possible to advance the theory, however, that this groove constituted the support for the planking of the centring, which as a result turned out perfectly formed and placed at the right distance from the lower edge of the arch and furthermore, it did not require complicated or robust props, which consequently here too became much reduced in dimension, much easier to make, and more straightforward and quick to erect and dismantle. To assist the adhesion of the concrete, it would have been sufficient and certainly much faster to break up the surface of the travertine at some points with a pick, even quite irregularly, in order to create some roughness on the surface. Furthermore, in an arch towards the Fori Imperiali, again on the third tier, there is a correction visible in the groove cut into the arch (Fig. 14), made in the course of the works. Obviously there would be no reason to make any such correction if this working of the stone was intended solely to favour the adhesion of the concrete and was destined to remain concealed.

Returning to the ribbing, it should be pointed out that in its early days the technique of constructing vaults in concrete counted on a preliminary structure



Figure 12
On the inside of the travertine arches on the third tier, note the grooving around the arches

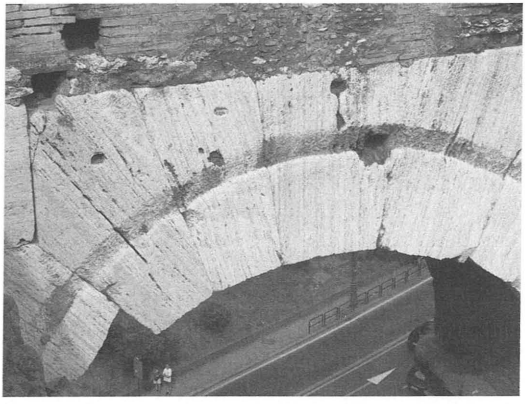


Figure 13
We can put forward the hypothesis that these grooves provided the support for the planking of the centring, which as a result was more easily realised



Figure 14
In an arch located towards the Fora, again on the third tier, there is a correction in the groove cut into the face of the arch, made during the course of the works. Obviously there was no reason to make such a correction if this operation was carried out exclusively to aid the adhesion of the concrete and therefore would have remained concealed

made up of large slivers of calcareous stone, placed on the centring and arranged radially, which remained embedded inside the concrete; therefore the insertion into the vaults of brick elements in the form of arches results from the technological evolution relating to the use of brick. It is not to be excluded that another function of the ribs, with respect to those already illustrated, could be to channel the forces within the most rigid and resistant elements, that is precisely the arches in brick, resulting in a concentration of the loads on the most rigid parts of the structure, as already shown with regard to the travertine piers present inside the tufa walling, but also because of the shrinkage of the mortar during the setting and hardening phase, which caused a concentration of the loads on those parts whose volume remains unchanged with the passing of time.

It is clear that the Romans were aware that the lines of force that run through masonry masses, due to vertical loads and horizontal stresses, both in the elevations and in the concrete vaults, never diffuse in a random, indifferent manner, but rather they follow very precise rules. Load-bearing arches, ribbing, piers in a more solid stone inserted within the walling, the carefully arranged horizontal positioning of the stones and of the fragments inside the concrete are all proof of such a knowledge, which, if not exactly scientific, was certainly technological.

Finally, we feel we can advance the hypothesis that the ribs and the links between them in bipedal bricks (a two-foot square brick) could also have the function of distributing as much as possible the effects of the shrinkage of the mortar, which if subdivided into many different sectors would be negligible, while for large single volumes it could create serious problems of cracking in the concrete block. It is to be believed that the Roman builders must have been particularly aware of this problem, since a careful observation cannot miss the fact that the solutions adopted to remedy the problem reached high levels of refinement and perspicacity. But, furthermore, it is perhaps from this viewpoint in fact that we can also explain the use (not yet sufficiently justified) of *opus reticolatum* placed at 45°, not present in the Flavian Amphitheatre but widely diffused in the following decades.[7]

Even the procedure of which mention has been made of realising the vault with sheets of bricks in several layers —a solution moreover adopted at the Colosseum (Fig. 15)— would support the theory of

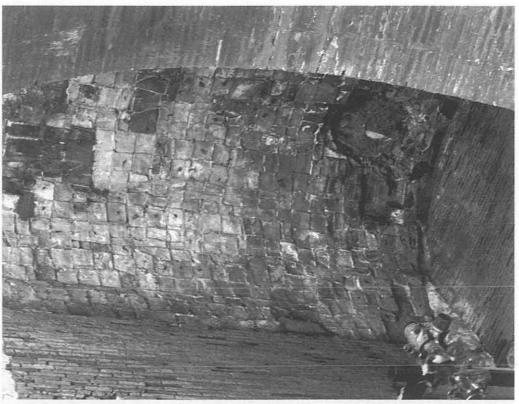


Figure 15
A barrel vault, on the first tier, with bricks laid in sheets on the intrados of the vault. These bricks probably formed a preliminary vaulted structure, allowing a reduction to be made in the dimensions of the wooden centring

the necessity of lightening the load-bearing function of the wooden centring and of simplifying it. In fact just as soon as the first layer of the vault was realised, which was very light and quick to execute since it was carried out with a quick-setting mortar and with a minimal centring, work proceeded to get the second layer under way, which could already make use of the support and the shape provided by the layer beneath, together with which it constituted a heavier and more robust structure as well. The same counted for the third layer, until a vault capable of supporting the weight of the mass of fresh concrete placed on top of it was obtained, the whole procedure achieved with a centring that, practically speaking, had the measurements necessary for just a thin sheet vault.

Probably the frequently used superimposed arches (with two arches placed one above the other and sometimes more)[8] also follow the same criteria: only the first arch was intended to be carried on the wooden centring, which, therefore, could have much reduced dimensions. Furthermore, the bipartite and tripartite horizontal division did not diminish the carrying capacity of the structure since it was completely compressed, unlike that which would have happened in the case of trabeated systems.

Similarly, for the execution of the foundations —comprised of an impressive oval *platea* (greater

diameter 188 metres, smaller diameter 156 metres) with an oval hole in the centre of an average depth of 13 metres— work proceeded in such a way as to save a considerable amount of time in the execution. In fact the foundations were not executed by means of excavation, which would have necessitated an enormous operational undertaking, but by building upwards, then filling in the adjoining areas with soil and rubble brought from the surrounding zones (Cozzo, 1971, 24; Giuffrè, 1988, 123). This structure, in concrete with fragments of hard volcanic (leucitic) stone, which was particularly solid, dense and impermeable, took the place of a natural trough that was occupied —as is well-known— by a small basin that collected water coming from the hills, the so-called «Nero's Pool». The Neronian structures, porticoes and buildings that rose up around the pool were buried in the made land around the perimeter. The foundation platform, bounded at its edges by a mighty wall in concrete and brick some three metres thick,[9] constituted a very solid and impressive base in relation to the particularly yielding, marshy ground, which over the centuries has caused differential subsidence in the part towards the Celio.

The piers of the first order do not rest directly on the foundation *platea* but on high stone plinths buried in the foundation. These plinths are noticeably wider than the piers set upon them and as a matter of fact, on the ground storey the offset that these create is visible at floor level.[10] Between the interred plinths and the piers, there is an adjustment of some centimetres, from which it can be deduced that only at the moment of realisation of the part above ground, was attention given to the accurate measurement and placing of the piers. Once again it is apparent that attention and care were given only where and in the moment in which they were considered necessary, or rather in the parts of the building that were in sight.

Another question which can be analysed from the viewpoint of the builders' desire to simplify the construction process wherever possible in order to achieve greater building efficiency is that of the planimetric layout of the geometry of the monument. Some hypotheses consider the geometry of the Colosseum to be an elliptical form; others consider it more probable that it is a polycentric, ovoid curve. The distinction is not simple to make since, in the Flavian Amphitheatre, these geometries are superimposable but for a few tens of centimetres. Certainly the polycentric curve is easier to lay out, easily manageable on the building site and more compatible with the fact that the ambulatories have a constant width. Even the laying out of the radial walls turns out to be more immediate. With the use of a geometry governed by polycentric curves, all of the construction, and therefore the positioning of every single block, on the superimposed levels as well, turns out to be more easily controllable from positions and sights placed at particular points.[11] (Fig. 16) What motive could the Romans have had to prefer a more complex form if it differed so slightly from another that was more easily manageable? Furthermore, the most precise surveys have confirmed the polycentric nature of the curvature.[12]

Another aspect that we should point out here is the static efficiency of the morphological configuration chosen for the façade. The presence of external offsets between the superimposed orders is, in fact, particularly appropriate to the objective of a greater solidity. It is apparent from the graphic renderings of the sections, but even to the naked eye observing the curved façade tangentially, that the line of the façade of every order is set back by a few tens of centimetres with respect to the order below. This configuration, which is also canonical in the superimposition of the orders, guarantees as far as possible that the vertical loads, to which are added the horizontal outward thrusts due to the vaults and, in the event of earthquake, those due to the horizontal accelerations, exert stress on the piers, at their base, in the most axial manner possible and therefore in the manner in which they offer the maximum solidity, thereby averting the eventuality of triggering mechanisms of collapse by overturning or the eventuality of exceeding the resistance of the material owing to the narrowing of the active section due to eccentric loading. As a result the external circle is braced towards the inside by the radial walls and towards the outside by this slightly stepped configuration of the façade, as well as by the curved form of the plan. In the case of the Flavian Amphitheatre, the offsets —which in buildings are generally present towards the inside so as not to be visible and in order to have a flat façade— reinforce the external walls and enhance the effect of solid stability which Piranesi grasped so well in his striking representations of the Colosseum.

Another factor relevant to the speed of the works was the mechanisation of the building site. The

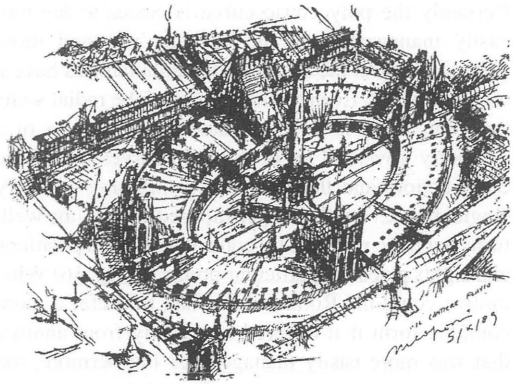


Figure 16
The ancient Flavian valley of the Colosseum. (Illustration 1989 and text by Piero Meogrossi)
This «reconstruction» of the Colosseum illustrating a possible but imaginary situation, circa 73–74 AD, depicts the valley (and its older drainage system supplied with natural springs) transformed by Vespasian's project and completed by Titus, who put into practice their desire to cancel out the previous Neronian structures and therefore also the memory of Nero's Domus Aurea itself.
The initial building works for the Flavian Amphitheatre appear to have taken into consideration, as important pointers, the topographical and urban landmarks of ancient Rome.
The Augustan *Meta Sudans*, the lowest point of Rome's water level, was intended by the Flavian engineers to become a fountain at a height that allowed water to be brought to the first storey of the Colosseum; while the *Sacellum Streniae*, a sacred site which marked the beginning of the Via Sacra, was probably maintained in connection with the outer limits of the site which would later be occupied by the Arch of Constantine.
These elements, which are fundamental and sustain the area of the amphitheatre, are in practice a series of sacred places which still remain bound together today by a greater topographical rule, the geometric measurement of which is consistent with the seasonal sun date of the XI *Calendas Maja* (which corresponds to the current 21 April, the anniversary of the foundation of Rome.)
For this reason it seemed important to preserve such signs or pointers and to link them together in order to determine the new relationships which moved around the topographical structure of the Colosseum itself.
In the drawing one notes the oval geometry that forms the Flavian monument under construction, the design of which must have been based physically on a central point set in position upon four focuses, all corresponding to as many towers linked in their turn to a central «betilum» tower (which probably was already present at the centre of the Neronian valley), a sort of solar clock reused as a base for the topographical control and three-dimensional construction of the building.
In the drawing one observes the ideal reconstruction of the four sectors, which advance progressively into the space and make use three-dimensionally of the wooden guide structures that serve to control the dimensions of the oval as it grows; at the same time, those instruments, put together on the building site according to a law based on the relationship 3–4–5, ensure mobility inside the area and the many related measurements that mark out a geometry made of regular lines that allowed the various corridors of the amphitheatre to be laid out.
Many working machines (the so-called *polyspastoses*) move all over the place in order to transport heavy materials and to raise the fabric of the Colosseum, while inside as outside the valley, which is not yet completely organised, there appear buildings of a public nature which represent an ample piazza organised on three sides with a portico or *porticus* on three levels.
The geometry and the distribution of such a *porticus triplex miliarensis* (as it was recalled by Tacitus) represent the appearance of a public architecture that exceeded by far the Neronian valley, which once had been characterised by its private nature and for having at its centre the private lake of Nero's palace.
The drawing shows the foundations of the Colosseum (about 13 metres high, a continuous oval enclosure which filled in the former Neronian lake leaving only a central hole) and it shows how the four towers for measuring the building site have been mounted artificially so as to make it possible to control the raising up of the different sectors of the building in accordance with the geometrical design.
By continuously measuring at different heights, these towers made it possible to remain perfectly in line with the topographical rule that crossed the entire valley and to maintain the Pythagorean relationship 3–4–5 that created the oval form of the Colosseum. Several fires placed at a distance marked out the sacred rule through Rome and allowed the construction to follow the principal topographical measure that crossed the valley and designed the *forma urbis.* (Meogrossi, 1993, 81–90).

Romans were capable of building complex machines for the raising of the blocks, which, even if made only of wood, through a system of levers, winches and hoists allowed even quite considerable loads to lifted. Most probably the inclined surfaces constituted by the top of the radial walls that supported the cavea, as well as slopes built up with filling material and rubble, provided surfaces along which building materials could be drawn upwards and thereby played their part in the transport and lifting of the blocks.

As to the enormous blocks of travertine, these were assembled with the use of lifting machinery of various types: in almost all the blocks there are conspicuous holes to allow them to be hooked up. Before laying every single stone in position, the surface of the block underneath was smeared with a thin layer of liquid lime mortar: this fluid layer aided the sliding of the masses one against the other and, at the same time, rendered the parts in contact more cohesive (Lugli, 1957, p. 243). Furthermore, this mortar layer clearly also had the important function of distributing the loads on the entire horizontal section, thereby avoiding dangerous concentrations on limited areas due to the fact that the corresponding faces of the blocks were not always perfectly flat. Moreover, metal pins were placed in appropriate slots cut into the faces of the blocks. Finally, the positioning completed, molten lead was poured into special channels carved into the lower block that conveyed the lead to the pins already positioned inside, which by this means were fixed effectively in place. That multitude of holes currently visible on all of the travertine façade of the monument are the traces of the laborious operation carried out during the Middle Ages to retrieve the metal materials which were particularly sought-after in that period. But for what motive did the Romans occupy themselves with such care to pin every single block? What important compensation did such a precise and widespread operation have? Was the strong friction owing to the high loads in play at the point of seizure between the blocks not sufficient to render the masonry sound?

According to some authors, the ties avoided relative shifts between the blocks during the phase of construction when, in the absence of loads above and in the setting and aligning of the upper blocks, unwanted displacement was still possible. But this theory loses its force if one considers the method of assembling and aligning through the use of lifting instruments and also the facilitation constituted by the liquid mortar of which mention has already been made. The objective of achieving a static reinforcement of the structure would seem to be excluded as well, taking into account the high values of the friction.

The only situation in which the effect of the friction could diminish to the point of failing is in the event of earthquake. The subsultory oscillations can, in certain instances, diminish the effect of the weight force and the vibrations of the structure can make the adhesion or bond between the faces of the blocks fail, even if for very brief periods of time. In these situations the effects of the undulatory oscillations can cause single blocks to become dislodged with respect to the blocks around them. It is clear that the presence of the pins could have had the precise function of preventing such circumstances from happening, in so much as they exercised an effective tie, which, resisting the shearing stress, opposed the relative horizontal displacement. Put more simply, it can be assumed that the Romans had observed the effects of earthquake on the masonry of older monuments in *opus quadratum* and, consequently, they opportunely found, or at least used in a systematic fashion, the most effective measure to prevent the occurrence of such serious damage, which was moreover irreversible once it had happened.

Notes

1. This paper fits within the compass of the research undertaken by the author for the Doctorate in *Tecnologie dell'Architettura* at the Univerisità «La Sapienza» of Rome with a final thesis entitled *Interventi di restauro sul patrimonio archeologico romano: tecnologie e metodologie*, as well as in the sphere of the *Gruppo per la Ricerca Storica sul Colosseo* commissioned by the *Soprintendenza archeologica di Roma* to the *University of Roma Tre*.
2. From 71–72 AD until 80 AD, the year of the inauguration. See Lugli (1971), 11.
3. The alternative suggestion that the duration of the works was three to four years, from 76 AD to 80 AD, is improbable. See Cozzo (1923), 275.
4. Cozzo (1971) has pointed out how the travertine was worked as little as possible on the building site to speed up the execution of the works. For this reason, the stone courses have different heights and the blocks intended to be buried have very irregular dimensions. See Cozzo (1971), 29–30. On the working of the blocks on site, see also Lugli (1957), 1: 332.

5. Lugli hypothesizes an initial huge framework of pilasters and arches in travertine —«enorme ingabbiatura di pilastri ed archi in travertino» (Lugli 1957, 1: 331–332)— on which it was possible for work to proceed with different teams of builders working contemporaneously.
6. All the measurements were made using a module (or *modula)* and fractions were avoided wherever possible. See Pearson (1975), 88.
7. «The most fitting justification seems to be, however, that which begins from the consideration that the arrangement of the blocks set at 45° ensures that every «easing» owing to the shrinkage of the mortar during the period of its setting, is easily aided and compensated for by small, gradual vertical shifts in the structure, assisted by the load itself, which recompacts the masonry before the mortar hardens, without the formation of vertical cracks. More simply, one could say that the diagonal disposition at 45° generates an effect of horizontal precompression of the structure, which averts the formation of vertical cracking during the phase of setting and hardening». See Giovanni Manieri Elia 2002.
8. Among the many examples, we can cite the *Terme di Caracalla*, or the load-bearing arches at the *Pantheon* in Rome or at the *Terme di Cellomaio* at Albano.
9. On the form, location and materials of the foundations, see Coarelli et al. (1999), 104.
10. With regard to the «pillars of foundation», see Cozzo (1971), 22–25.
11. Piero Meogrossi, within the context of a polycentric geometric configuration, the principal axes of which identify precise and significant directions that relate to the form and history of the city, suggests the presence during the phase of construction of a «torre-obelisco-traguardo e regia, alta e centrale», that is, a tall centrally-placed tower used for taking sights in order to control the geometric layout of the building. See Meogrossi 1993.
12. This is the conclusion arrived at by the group of researchers coordinated by Mario Docci. See Docci 1999.

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The baroque Roman building yard: Technology and building machines in the reverenda fabbrica of St. Peter's (16th–18th centuries)

Nicoletta Marconi

The triumphal raising of the Vatican obelisk between April and September 1586, commissioned by Sisto V Peretti (1585–1590) to Domenico Fontana (1543–1607), starts a process of innovation and improvement in the building technology, heir of the Roman-imperial mechanics, which will reach a level of efficiency and functionality between the XVI and XVII Century, for a long time unsurpassed. What is the main contribution of the experimentation of Fontana to such technology, which persists at least up to the XIX Century? This experimentation is supported by the new impulse in the Roman building of the XV Century, as well as by the renewed interest for the mechanics, intended to create more functional and modern devices. In addition, it contributes to the development of an extraordinary organizational and technical system for building management, based upon the ingenious mechanism of the Reverenda Fabbrica of St. Peter's and the entrepreneurial character of the masters of Lombardia, able to conjugate the Gothic constructive ability to a wise management of workers. From the first half of the XVI Century to the first half of the XIX Century, the Fabbrica is the real propeller of the Roman building economy. It is the institution assigned to control of the financial and technical administration of the Vatican building yard, similar to the «Opera del Duomo» in Florence or the «Fabbrica di St. Petronio» in Bologna (Basso 1987; Haines and Riccetti 1992, XI; Conforti 2001, 16). The Fabbrica of St. Peter's can be considered a government institution, a technological and experimental workshop and a qualified school for skilled workers, at the same time. It is managed like a modern building enterprise, with a rigid hierarchical structure, and has at its disposal a large amounts of materials, tools and building machines, the so-called «munitioni», accumulated in centuries of building activity and stored in at least five stores inside the Basilica. These provisions have been accumulated from the period of Michelangelo's supervision up to the construction of the portico, and also later. The purchase, use and loss of tools and materials are recorded in many documents of the Fabbrica of St. Peter's. From the half of the XVI Century, the cardinal congregation supervising the Fabbrica develops a ingenious system for the hire and sale of these tools and materials, as well as for the «loan» of qualified manpower, the minor building yards. In this way, they can face the economic load required by the use of the big building machines, the purchase of expensive lumber and metal for construction, the provision of richer materials, like freestones and ropes (Rice 1997). This system is structured as follows: initially, the material to rent is carefully estimated and measured, then delivered to a representative of the applicant building yard, who becomes personally responsible for returning the material at the end of the works. Once returned, the material is re-estimated, to assess the wearing caused by use. In case of partial damage or complete uselessness of the material, a penalty is applied to the initial price of the hire, corresponding to a percentage

up to the complete value of the object, depending on the gravity of the situation. The difference between the initial and final estimation of the material represents the debt contracted by the minor building yard with the Congregation of St. Peter's. Furthermore, all the materials remaining from the minor building yard, also those acquired from other suppliers, are purchased by the Fabbrica of St. Peter's and added to its inventory. These exchanges sometimes enrich the Fabbrica considerably: between 1653 and 1654, the sale to the Sant'Agnese building yard of 164 pieces of travertine, coming from the demolition of the bell-tower of St. Peter's (1647), yields to the Fabbrica around 4,000 *scudi*. A similar amount is obtained in July 1662 by the sale of the columns of same bell-tower, which are used for the churches of *Piazza del Popolo*. The meticulous estimation of the material also allows to understand the technical and constructive difficulties encountered by architects and workers during the works. The history of the objects concerns some of the most famous building yards of the Baroque Rome, like the Fabbrica of Santa Maria della Pace. For the frescoes of its dome, all the purlins, the boards of ilex, chestnut and elm wood, and the iron stirrups necessary to build the scaffoldings for the painters are taken on loan from the Fabbrica of St. Peter's on 20th November 1650 and returned on 13rd March 1665.[1]

In this system, the building technology, and particularly the building machines, have the most important role; in some cases they represent the only subject of the agreements between the Vatican Fabbrica and the minor building yards. What is the status of the building technology at the end of the XVI Century? The building machines, as shown by the treatises and the architectural iconography of this period, are quite similar to the ancient ones, like levers and chutes used by the Egyptians during the third millennium before Christ, or the building machines in use at the time of the Imperial Rome (Cupelloni 1996, 54).[2] Nevertheless, a new interest for the applied mechanics appears in the XV Century, noticeable through the study of the X book of the *De Architectura* of Vitruvio and in the invention of spectacular and bizarre machines. A very famous example are the «alzacolonne» of Francesco di Giorgio (1439–1501), to whom Vasari attributes the revaluation of the *machinatio*, an integral part of Architecture (Fiore 1978). However, the technicians stile prefer to improve the devices verified in centuries of practice, in particular the building machines developed by Filippo Brunelleschi (1377–1446) for the dome of Santa Maria del Fiore in Florence, Mariano di Jacopo called the Taccola (1381–1458), Bonaccorso Ghiberti, Giuliano da Sangallo, and Leonardo da Vinci (Taccola [1427/1433] 1969, 14v–14r). These machines, assembled with gear wheels, endless screws, racks and winches, also used for the hoisting and transportation of columns, obelisks and pyramids, reveal a considerable technical maturation. However, only Domenico Fontana will be able to create a really efficient apparatus, thanks to his extraordinary technical talent and to the resources made available to him by the

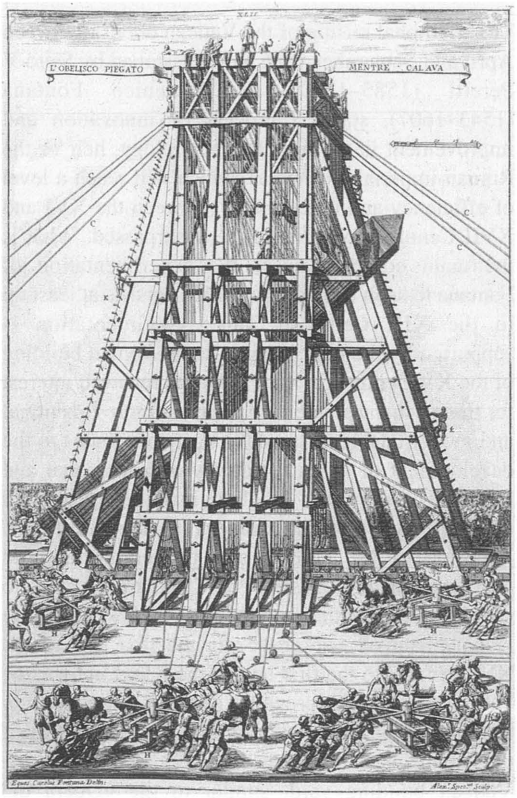


Figure 1
The scenographic scaffold designed from Domenico Fontana for the raising of the Vatican Obelisk (Zabaglia 1743, fig. XLII)

Fabbrica of St. Peter's. The scaffolds and building machines developed by Domenico Fontana for the removal, transportation and raising of the granite obelisks, either monolithic or «fracti», are conceived in a way that they can be applied also to the common practice. This is particularly true for the machines and tools used for the erection of the Vatican obelisk (Figure 1). Although initially acquired by the Fabbrica of St. Peter's with a big economical effort, then will represent for the Fabbrica a very precious property for the following three centuries. Either used for the raising of other Sixtine obelisks (1587–1589) or rented to other building yards, they are a real source of gain. To raise the Vatican obelisk, having a weight of 400 tons, forty winches, five 15 meters long levers and 139,000 pounds of ropes are used (Figure 2). The iron tools, like pulleys, hammers, tackles, nails and rivets, partly come from the stores of the Basilica, partly are fused either in the papal foundry of the Fabbrica, or in the foundries of Ronciglione and Subiaco (Fontana C. 1694, 475–476).[3] The papal foundry, located near Santa Marta in Vaticano, is used to make the «traglioni», big tackles in iron with six or four swivel joints, requested by Fontana. For their fusion, around 10,000 pounds of metal are used in addition to a large quantity of firewood (D'Onofrio 1992, 475–476). Most of the lumber used for scaffolds, «curli»[4] and other machines comes from the woods of Nettuno, Terracina and Santa Severa, property of the Camera Apostolica (Fontana D. 1590, 6–7).

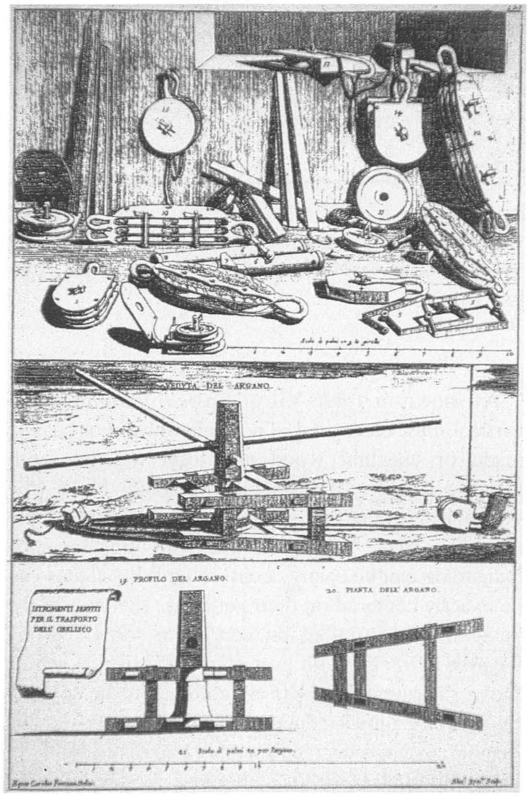


Figure 2
A.Specchi, Hoisting tools, winch and tackles used in erecting Vatican Obelisk (Fontana C. 1694. 127)

Due to the poor quantity of lumber available in the Roman country, the supplies must be optimized, the quantities must be exactly assessed, the process wastes must be strictly controlled, and the lumber re-used where possible. To have an idea of the complexity of the scaffoldings, the one supporting the Vatican obelisk can be considered. It is composed of eight big masts («candele»), each one consisting of four wooden beams, joint together and tied up with ropes and metallic belts. There are four masts each side of the steeple. This structure is strenghtened by a complex frame of braces, struts and trusses, and smaller beams placed either normally or parallel to the masts, in order to stabilize the structure and prevent the oscillations and the bending when the tackles are in use. The structure is also stabilized by eight ropes of big diameter, called «ventole», fixed to the top of the structure and anchored to stakes on the ground.

However, most of the building yards of Renaissance and Baroque have no need for such a complex technology, and use more traditional devices. This technology remains substantially unchanged up to the half of the XIX Century, when major modifications will be caused by the introduction of new materials, like cast-iron, or the use of electrical power. Until these changed are introduced, all the winches, «burbere», capstans, masts, gins and gin-poles, are made with wood and hempen ropes. Since very expensive, the use of metal is strictly limited to the manufacture of those parts subject to efforts and wearing, like tackles and pulleys.

The traditional character of the building technology of Renaissance and Baroque is evident from the inventory of the Fabbrica of St. Peter's, as well as from the reports of other roman building yards. An

example of traditional building machine is the «antenna», a sort of wooden crane, either fixed to ground or mounted on a moving platform on four wheels. The «antenna» is connected to a winch, operated by twelve workers. Anther person is responsible for winding the free end of the rope; other two control its tension. Also the «antenna» is stabilized by means of three or four «ventole». The stone blocks are lifted by means of a hoist composed of two tackles with four turns of rope. A picture of an «antenna» on wheels is shown in an anonymous drawing representing Palazzo Farnese under construction, at the time of the supervision of Antonio da Sangallo the younger (1483–1546)[5] (Figure 3). The drawing is in contrast with the opinion of Filippo Maria Renazzi, editor in 1824 of the *Castelli e Ponti* of Nicola Zabaglia (1743), according to which Zabaglia was the first inventor of the «antenna» on moving base (Renazzi 1824, VI-VII). The «antenna» of Zabaglia is used in 1703 to position the 50 travertine statues of the St. Peter's portico, work commissioned by Clemente XI Albani (1700–1721) and completed in only three months with only the help of young workers (Figure 4).

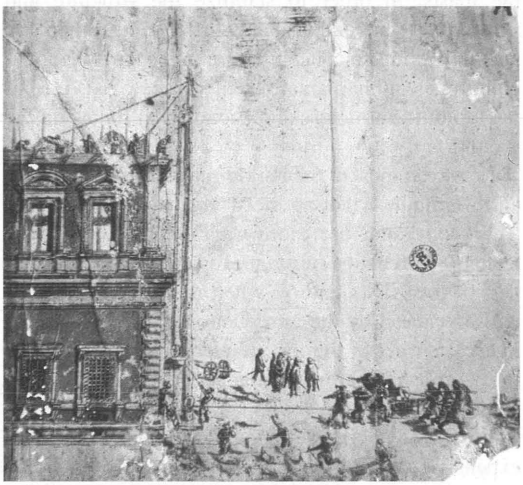


Figure 3
Anonimous, The building yard of palazzo Farnese at the half of XVI centuries (detail). On left side is visible the «antenna» (mast) used for lifting materials and stone blocks on the scaffold (Naples, BNN, Sez. mss e rari, ms. XII. D. 1. fol. 8)

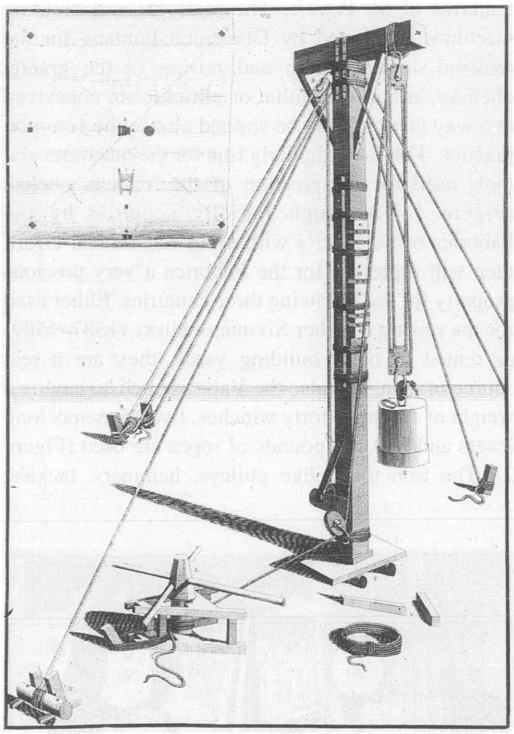


Figure 4
The «antenna» (mast) designed by Zabaglia for installing the 50 statues of the St. Peter's Portico in 1703 (Zabaglia 1743. fig.VII)

As shown in Table VII of *Castelli e Ponti*, it is a vertical mast composed of a number of minor beams, made of chestnut wood and joint together with metallic stirrups. It bears an horizontal beam (the «falcone») on the top, supporting the hoisting tackle (Marconi 1998, V 46–52). With this «falcone» the balustrade can be easily accessed and the statues can be exactly centered on their pedestal. The base of the «antenna» is installed on «curli», a sort of strong wooden cylinders with iron rings at both ends, which move the antenna's base by rolling on the ground. Such device allows reducing the costs in a considerable manner, as it avoids the assembly and disassembly of the traditional scaffolds, otherwise required for the installation of each statue. Due to the considerable height of the statues (3 meters) and of the portico (17 meters), the «antenna» is stabilized by four «ventole»,

two manufactured ad hoc for the work, two taken on loan from a «funaro» of the Fabbrica of St. Peter's.[6] The statues are raised by means of a big winch and a capstan made of ilex wood, mounted on the base of the antenna. Zabaglia analyses accurately each phase of the process, in all details, even the way to twist the ropes around a statue. For this purpose, he makes a small gypsum model of a statue, wrapped up with ropes, still preserved in the store of St. Peter's.

However, in the common building yards the hoisting machines in use are frequently simpler. They can be «burbere» or capstans, small horizontal winches with tackles to raise wooden buckets containing various materials (Marconi 2001, 108–112). Also the gin («capra») is frequently used, either in the open or the closed version. It is composed of a wooden trestle supporting a hoist and a winch, and is used to lift big stones and statues, as well as to unload the big blocks of travertine and marble coming from Tivoli and Carrara, on ships sailing along the Aniene and the Tevere. The closed version of the gin consists of three masts linked together at one end with ropes, supporting a tackle (Figure 5). The rope of the tackle is connected to a winch fixed to the base of two of the three masts. On the contrary, the open version of the gin is stronger and of bigger dimensions. It consists of a trestle whose horizontal crossbar supports the tackles operated by winches (Figure 6).

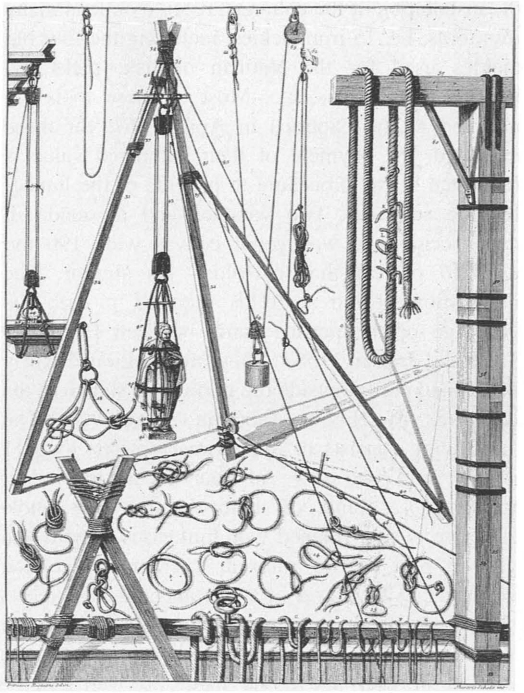


Figure 5
The closed version's gin, used in Renaissance and Baroque building yard for raising stone blocks and statues (Zabaglia 1743. fig. II)

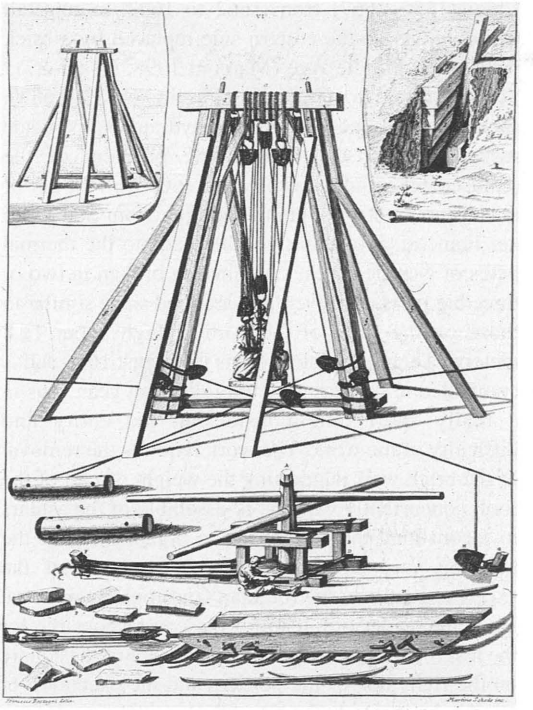


Figure 6
The open version's gin, used for lifting massive stones (Zabaglia 1743. fig. VI)

«Antenne» and «capre», the most common hoisting machines, are already described in *De Architectura* of Vitruvio, as well as in *De Re Aedificatoria* of Leon Battista Alberti (1485), and also in the drawings of Nicolas Tessin the younger. In particular, Tessin describes two of the «antenne» of the Fabbrica of St. Peter's rented to the building yard of Sant'Agnese in

Agone at the time of the supervision of Francesco Borromini from 1654 to 1658. For this work, commissioned by the Pamphili family, the Fabbrica also provides 166 iron stirrups, iron lifting pins, a «burbera» for the dome's scaffolding, «curli», pulleys and tackles, and other minor tools.[7]

The primary role played by the Fabbrica of St. Peter's in the Roman building is evident from the analysis of a number of significant building yards.

One is that started up for the restoration of the Pantheon's portico, commissioned by Alessandro VII Chigi (1655–1667) from 1662 to 1667, to reinstall two columns on the eastern side replaced by a brick wall in the Middle Age (Marconi 1998, VI 63–87).[8] The Dominican Giuseppe Paglia (1613–1683), specialized in mechanics and hydraulics, is made responsible for this work. The problem of the replacement columns is solved in 1662 with the use of two columns of pink granite coming from San Luigi dei Francesi, probably traceable back to the thermal baths of Nerone. These columns are broken in two or three big parts, however they are used since similar to those on the front of the portico, high about 11.8 meters[9]. Their installation starts in August 1666 and is completed in the spring of the following year, thus in a really short time considering the entity and difficulty of the work. The work requires the removal of the brick wall, supporting the weight of part of the roof, concurrently with the re-assembly of the ashlars to reconstitute the columns. The organization of the building yard is evident from a synthesis of the expenses made by the foreman Giuseppe Bucimazza. He is the leader of a team of masons responsible for the leveling of the ground, the pavement of the square on the right side of the portico, and the execution of all the brick-works; while all the stone-works are assigned to three different teams of stonecutters, variously qualified. Sometimes they supply considerable amounts of travertine from Tivoli, the most precious. The manufacture of scaffoldings and hoisting machines is mainly assigned to masons and stonecutters, rather than to carpenters. Considerable is the entity of the economical effort required for the works. The summary of the expenses of 26th November 1666, only relevant to the works for the square, reports an expense of around 9300 *scudi.*[10] This summary also shows the difficulties encountered to assess the cost of the scaffoldings and for the assembly of the columns. The costs involved are so onerous as to require the support of the Fabbrica of St. Peter's to continue the works. Without such support, the foremen have to personally provide all the tools, machines and scaffolds, and are constrained to surcharge their fee. In particular, the provision of three ropes supporting up to 7000 kg and required for the stabilization of the scaffolds has a prohibitive cost.[11] One of these ropes is long around 290 meters and has a diameter of 19 cm: the resort to the Fabbrica of St. Peter's is therefore inevitable.[12] The Fabbrica, also thanks to the intermediation of the Pope, supplies all the required materials and tools, and undertakes to pay for the manufacture of these ropes, provided that on completion of the works they become property of the «munizione generale di San Pietro e di Castello».[13]

In November 1666, the responsible for the stores of the Reverenda Fabbrica («fattore») delivers to Paglia «le robbe per drizzare le colonne del Portico dell Rotonda», like tackles, pulleys, and various cuts of lumber.[14] The stonecutters, who physically carry out the installation of the columns, receive on loan many iron tools, i.e. 15 iron tackles, including the four big tackles used for the Vatican obelisk, picks, 66 stirrups, lifting pins, etc. Most of these tools are returned to the Fabbrica in April 1667, for those damaged, the payment of their estimated value is requested.[15] The procedure to provide of the lumber for the scaffolds, two winches and a «tenda di canovaccio» —a waterproof canvas wide 190 mq used to protect the scaffolds— is similar. The installation of the scaffolds required to crib the coverage of the portico starts between December 1666 and January 1667. They are positioned partly below and partly outside the portico, as shown in the drawings of Nicola Zabaglia (Figure 7). The scaffolding consists of four primary masts, long 11 meters, and two rows of four secondary masts, supporting a frame of minor beams. The whole structure is strengthened with buttresses fixed to the ground and by an internal system of wooden stiffeners. Also a grid of ropes anchored to pickets stuck into the ground contributes to stabilize the structure. Once the scaffolding is completed, the portion of roof above the medieval wall can be removed and the wall demolished. The ashlars are then positioned in place, juxtaposed and joined together by means of iron dowels, sealed with lead. An adequate space for manoeuvring is made available

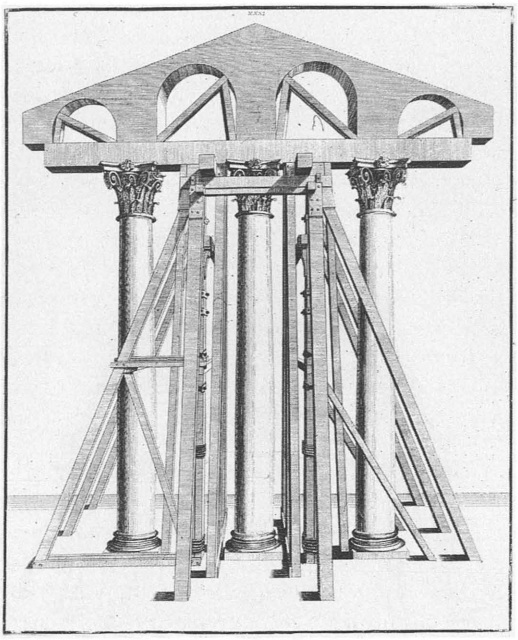


Figure 7
Frontal view of the scaffold comparable with the one used in reinstalling the two columns on eastern side of the Pantheon's Portico (Zabaglia 1743. fig. XXXI)

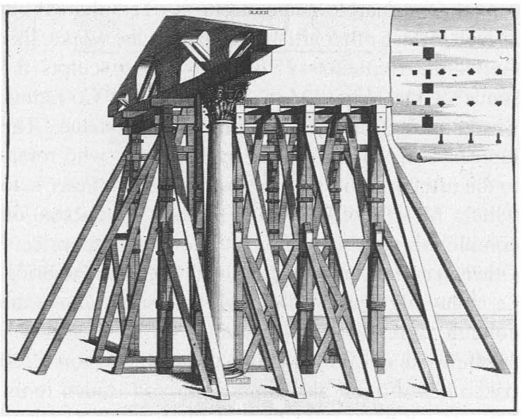


Figure 8
Lateral view of the same scaffold that Zabaglia awards to Pantheon's Portico (Zabaglia 1743. fig. XXXII)

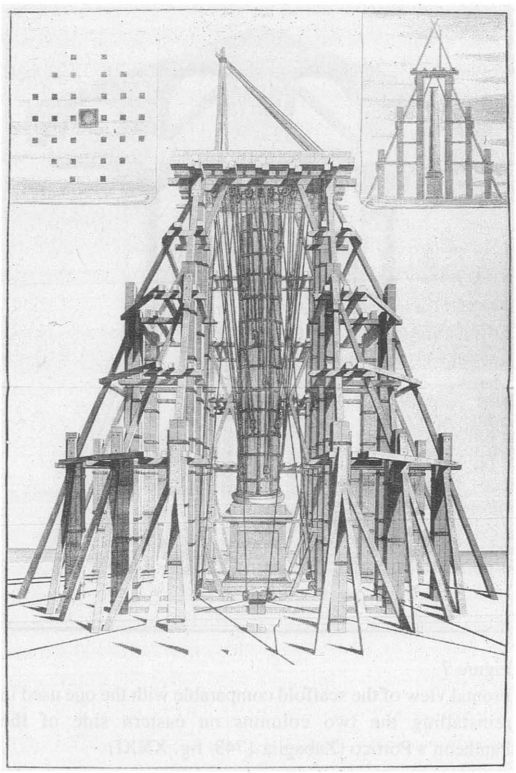
inside the scaffolding, to enable the oscillations necessary to correctly pile the blocks. The capitals are positioned finally. They are lifted up and slided horizontally to reach the correct position above the column. Then the roof is rebuilt, and the surface of the columns, the lintel and the capitals finished off. Once the restoration is completed, the scaffolds are gradually dismantled so as to allow the structure to recover its original static equilibrium (Figure 8).

The supremacy and the primary role of the Fabbrica of St. Peter's in the Roman Baroque building is also evident from the reports of the raising of two other monumental columns: one dedicated to the Virgin Mary in Piazza Santa Maria Maggiore (1613–1614), supervised by Carlo Maderno (1556–1629), and one dedicated to Antonino Pio in Campo Marzio (1703–1704), supervised by Francesco Fontana (1668–1708).

The raising of the column of Santa Maria Maggiore is one of the works promoted by Paolo V Borghese (1605–1621) to enhance the city of Rome. It has an urban function, that is to be a perspective focus for the square, like the obelisk of St. Giovanni in Laterano with which it is visually in contact, as well as a sacred function, that is the celebration of the Virgin Mary, through the statue installed on its capital. This column is a marble monolith of Corinthian order, coming from the Templum Pacis (or Basilica di Massenzio). The works are assigned to Carlo Maderno, not only because he is Architect of the Fabbrica of St. Peter's, but also for his technical preparation achieved in the building yards of Domenico Fontana (his relative) and especially in that for the Vatican obelisk.[16] The works begin in August 1613 and are completed after around a year, in June 1614.[17] The organization of the building yard of Maderno is structurally similar to the Fontana's enterprise, where teams of specialized workers and a rigorous planning of the jobs allow perfectly coordinating the all phases of the process.

The transportation and installation of the column is accomplished by the masons, with the support of sailors from the pontifical fleet for the operation of the ropes; also the realization of the wooden scaffoldings is assigned to the masons, but with the contribute of carpenters and blacksmiths. The stonecutters are responsible for the stoneworks and also for providing the marble necessary to restore the

capital. The marble comes from the Templum Pacis as well.[18] Also other artists take part to the works, like Guillaume Berthélot (1570–1648), who sculpts the statue of the Virgin Mary, and Annibale Corradini, who accomplishes the gilding of the statue. The lumber is provided directly by Maderno, who refers to the usual suppliers of the Fabbrica of St. Peter's, to which he'll resell all the lumber in excess on completion of the works, at the purchase price.[19] Other materials are taken on loan from the Fabbrica, i.e. many big «curli» of elm wood, used to move the column from the Fori to Santa Maria Maggiore,[20] 1160 planks of elm wood of various dimensions, 200 oaken boards, and also ropes, iron and leaden tools. On completion of the works, the ropes will be resold to the building yard of the Civitavecchia's port, while part of the lumber will be used for the port of Fiumicino. It is possible that also the six-pulley tackles used for the Vatican obelisk were provided by the Fabbrica. The column is wrapped up with wooden planks and ropes, in order to protect its surface and be able to hook the hoisting tools. It is lifted, then placed horizontally on a wooden sledge, and towed towards Santa Maria Maggiore by means of winches, hoists and 60 horses. Here the column is positioned at the base of the scaffolding, which is very similar to that made for the Vatican obelisk. By means of winches, each operated by 16 men, and tackles, the column is lifted and simultaneously rotated to reach the vertical position, then lowered and positioned on the pedestal, to which it is fixed by means of iron dowels, sealed with lead. The capital is installed finally. It is inserted horizontally in the space between the top of the scaffold and the column, then lowered and positioned on the top of the column (Figure 9).



Figures 9
Scaffold commonly used for raising monolithic columns, maybe comparable with the one employed for the Santa Maria Maggiore's column (Zabaglia 1743. fig. XXXV)

In 1703, another descendant of Domenico Fontana, Francesco Fontana, is commissioned to raise the column of Antonino Pio in Campo Marzio, in front of the Curia's palace.[21] This work can be considered one of the most sensational failures of the technology of the XVIII Century, as confirmed by analysis of the working process and the scaffolding used for the raising of this granite monolith from Assuan (Marconi 1999, 43–54). The analysis highlights the contrast typical of this period of transition between the outward trust in the new scientific research on one side and the continuous reference to the practice of the past on the other side, which is still the sole reliable instrument to control operational processes but is going to be forgotten and gradually unlearnt. The reason for failure of the raising of Antonino Pio's column can just be found in the concurrence of this fragility of mechanic science and the operational insecurity of designers and workers.

Although decisive in this case, the intervention of the Fabbrica of St.Peter's is not sufficient to prevent the failure of the works. The unsuccess is determined not only by the inaccuracy and lack of coordination of the manoeuvres accomplished, but especially by the erroneous position of the tackles on the top of the scaffold, which causes the supporting structure to yield in more points with consequent damage of the column (Figure 10). Neither the contribution of the Fabbrica of St. Peter's, nor that of Francesco Fontana, can prevent

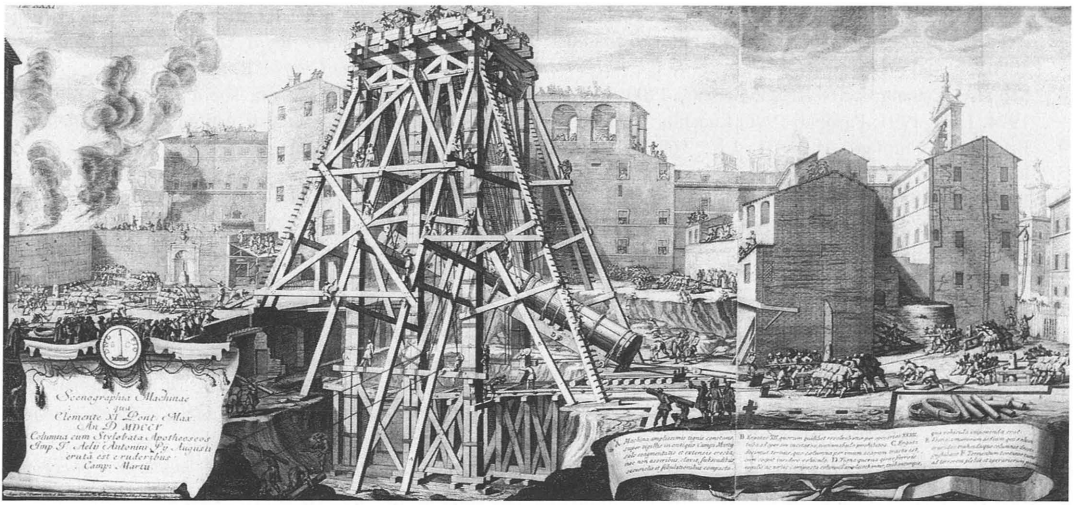


Fig.10
Spectacular scaffold and hoisting machines in the building-yard of Antonino Pio's Column in Campo Marzio (Piranesi 1762. fig. XXXI)

this failure. The Fabbrica supplies ropes, iron tools and lumber in large quantity, and sends the excellent foreman Giacomo Patriarca, follower of Nicola Zabaglia, together with Giacomo Visco, a blacksmith experienced in tackles and hoisting tools, and the carpenters Marcantonio Ravasio and Francesco Radice,[22] experienced in the repair of machines and scaffolds. For his part Fontana, now called «ingegnere», arranges a massive system of men and equipment: 520 workers, 13 specialized foremen responsible for the winches, vast sums of money for the provision of lumber, ropes, and «torce a vento», candles used to work at night. Nevertheless, despite all efforts, the column is damaged irremediably. It is abandoned in the square of Montecitorio until 1748, when its granite will be used for the restoration of the Augusto's obelisk.

According to the reports of the works, Francesco was not able to put into practice the teaching of Domenico Fontana, still considered the sole real authority in this field. Only Nicola Zabaglia, the «sampietrino» building foreman so called «ingegnere», will be considered a similar authority in the XVIII Century, although without the accomplishment of spectacular works. For a long time, he will represent an undiscussed model of technological skill, confirming the Fabbrica of St. Peter's in its role of main leader for the whole Roman building.

Archives abbreviations

AFSP = Archives of the Fabbrica of St. Peter's
ASR = State Archives of Rome
BAV = Vatican Library
BNN = National Library of Naples

Notes

1. AFSP. arm. 26. rip. E. vol. 393. 1r.
2. See also Usher 1954; Singer and Holmyrard 1957; Drachmann 1963; Hodges 1970; Gille 1980; Martines 1999.
3. In Carlo Fontana's treatise on *Templum Vaticanum* Alessandro Specchi shown the «Istromenti serviti per il trasporto dell'obelisco vaticano» (tools for the Vatican obelisk's raising).
4. The «curli» are a sort of strong wooden cylinders with iron rings at both ends, that move the building machines by rolling on the ground.
5. BNN, mss e rari, ms XI. D.1. fol. 8; Di Mauro 1987, 113–123. For information about Sangallo's drawings of building machines, instruments and tools, see Scaglia 1994, 81–94.
6. AFSP, arm. 27. rip. C. voll. 397, 402, 396, 390.
7. One of the «antenne» will not be returned to the Fabbrica of St. Peter's, since seriously damaged. Camillo Pamphilj will pay around 195 scudi to the

Fabbrica for this «antenna» and other scrapped tools (AFSP, arm. 7. rip. F. 466 and D'Amelio and Marconi 2000, pp. 406–418).

8. See also Fontana C. 1694, 473; Cerasoli 1909; Marder 1974, 1989, 1991; Pasquali 1996; Lucchini 1996.
9. BAV, ms Chigiani M. VIII. LX. 169r. See also Krautheimer 1985.
10. BAV, cod. Chig. PVII. 9.101, «Ristretto di tutto il denaro speso per il corrente giorno 26 novembre (1666) per il risarcimento delle due Colonne da rimettersi nel fianco destro del Portico».
11. To have an idea of the load capacity of this rope, consider that a rope of 5.5 cm of diameter has a load capacity up to 2000 kg.
12. BAV, cod. Chig. PVII. 9.101r.
13. BAV, cod. Chig. PVII. 9.102r
14. AFSP. arm. 26. rip. E. 303. 15r. «Libro dove si notano tutte le robbe che si prestano dalla Reverenda Fabbrica di San Pietro (1650–1685)». Further information are available in AFSP, arm. 26. rip. E. 337, 83–87, «Entrata e Uscita di Monitione 1659–1683».
15. AFSP, arm. 26. rip. E. 337. 83–84r.
16. Carlo was born in 1556 in Capolago, on the Lugano's lake, from Paolo Maderno and Caterina Fontana, sister of Domenico. Carlo becomes Architect of the Fabbrica of St.Peter's, together with Giovanni Fontana, in 1603, following the death of Giacomo della Porta (See Hibbard 1970).
17. ASR, Camerale I. Fabbriche. 1537, 250r–251v. See also Corbo A.M. and Pomponi M. eds. 1995.
18. ASR, Camerale I. Fabbriche. 1537. 266r.
19. AFSP, arm. 1. rip. A. vol. 2., 49.
20. ASR, Camerale I, Giustificazioni di Tesoreria. 39. f. 6. 4r.
21. Bianchini 1704; Cancellieri 1821; Crescimbeni 1705; Fontana C. 1708; Pellegrini 1881; Posterla 1705; Vignoli 1705; Vogel 1973.
22. From 1703 to 1704, Francesco Radice, foreman carpenter in the Fabbrica of St. Peter's, skillful in scaffolding and hoisting machines, is paid for the works «all'antenna che ha servito per mettere in opera le 50 staute di travertino sopra le Balaustrate avanti la facciata di San Pietro, tanto che avanti la caduta di detta antenna, quanto dopo» In 1704, he also accomplishes the restoration of the three moving scaffolds in the Basilica of St. Peter (AFSP, arm. 27. rip. C. vol. 396. «Registro delle liste di operai e spedizioni 1695–1725».

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The story of prestressed concrete from 1930 to 1945: A step towards the European Union

Bernard Marrey
Jupp Grote

The early history of prestressed concrete is almost entirely related to rearmament and the war effort, beginning in the early 1930s with the German preparations for the Second World War. For that reason, there are few records of the development of this technique: everything was top secret. We were fortunate to find a number of people who had lived at that time and who had a knowledge of the events in question. They provided us with a great deal of oral information, but in the meantime, all of them have died.

The story is somewhat bizarre. The underlying idea had been around for a long time, but it was Eugène Freyssinet who came up with the invention that allowed the idea to be put into practice. The French themselves showed no great interest in the invention. The Germans, on the other hand, wished to save steel for war (a war they were also to wage against France, of course), and the German company Wayss & Freytag obtained a licence from Freyssinet —only to use his system almost exclusively for the construction of bunkers.

Initially, the chief negotiator for Wayss & Freytag was Professor Karl W. Mautner, but since he was a Jew by birth, the Nazis soon removed him from all his offices. In the pogrom of 9 November 1938, he was arrested and detained in Buchenwald concentration camp for six weeks.

Sir Alan Harris —deputy head of P.C.C., the world's first prestressed concrete firm, and later a partner of Harris and Sutherland engineers— informed us that the London firm of Mouchel Engeneers invested quite a lot of money and obtained the help of the secret services of several governments to free Karl Mautner and get him and his wife out of Germany in the summer of 1939. Probably the most important contents of Mautner's luggage were the records of prestressing trials carried out in France and Germany.

These events led to the triumphant advance of this technology in Britain. There, too, it was initially used almost exclusively for the construction of bunkers and for girders in temporary bridge construction intended to repair eventual war damage.

There is good reason to believe that all the parties involved in these developments fulfilled their contractual obligations. Freyssinet provided the know-how, and the recipient companies correctly paid their licence fees. For at least one German bunker, concrete anchorage cones for the sheaves of tensioning wires were delivered from France in 1943–44, together with the appropriate jacking devices presumably. As a result, a collaboration between European building contractors was possible after 1945 without disputes about money and fees. These post-war developments parallel the emergence of the European Coal and Steel Community, which was formally established in 1952 and which may be seen as one of the predecessors of the European Union.

All's well that ends well, one might say. But there is also a tragic side to this story: alone on one German

construction site where prestressed concrete was used, more than a thousand men lost their lives through accidents, starvation, freezing working conditions and Allied bombing, Figure1.

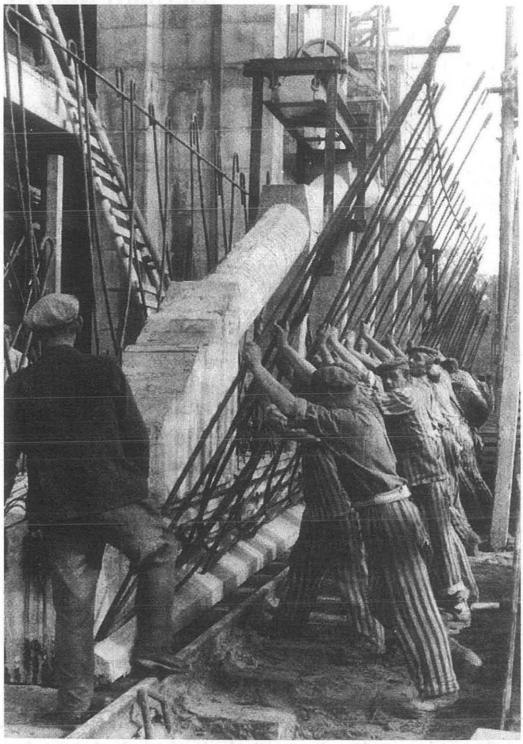


Figure 1
Concentration-camp prisoners insert heavy mild-steel anti-bomb reinforcement into prestressed stringbow truss at Bremen-Farge.

As a young civil servant responsible for engineering construction in the provinces, Eugène Freyssinet was placed in charge of the construction of three bridges across the River Allier in the early years of the 20th century. He was utterly convinced that these structures were so economical that they would be unrivalled in price. Freyssinet mistrusted calculations. He therefore ordered the construction of a trial arch with a span of 50 m, the abutments of which were tied together by high-strength stressed wires. Interestingly enough, one finds the same simple wedge-shaped anchor pieces he employed in 1907 being used in 1944 in the construction of a German bunker, Figure 2.

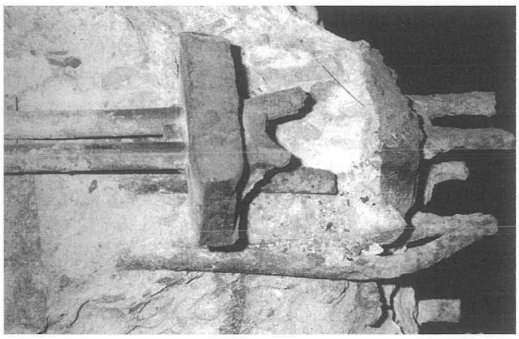


Figure 2
Anchor piece as developped by Freyssinet in 1907 chiselled in 1998 from truss of the bunker Bremen-Frage built in 1944. The neighbouring concrete anchorage-cones (not shown) are those invented by Freyssinet in 1939 and delivered for this bunker from Paris.

Freyssinet kept a keen eye on his building sites and structures. Noticing the dangerous deformation that occurred in the first three-hinged arch bridge, he compensated for it by forcing apart the joint at the crown. According to the theories held at that time, deformation of this kind was impossible. Creep and shrinkage in concrete were unknown, indeed, inconceivable. Only in 1928 was Freyssinet in a position to quantify his observations in such a way that, together with Jean Séailles, he was able to submit the first application for a patent for the manufacturing process of prestressed concrete. Despite the long-term deformation to which concrete is subject, the system functioned because the elongation lines of the high-strength tensioning wires were adequate to maintain the prestressing effect even after the concrete had shortened in length.

In 1928, however, no one believed it was possible to exploit this process commercially. All Freyssinet was able to produce were prestressed concrete pylons for electric power lines; and in view of the critical economic conditions prevailing at that time, even they were not profitable.

In 1933, with a courage —or foolhardiness— born of desperation, Freyssinet accepted the assignment of saving the transatlantic quay in LeHavre. The project was beset with risks. The structure was in danger of collapsing even before being completed because it had been overlooked that there was silt beneath the gravel foundations, Figure 3. The main elements of Freyssinet's solution were three large prestressed concrete girders, which he inserted beneath the structure, underpinning them with additional piles, Figure 4. Allegedly, these girders still form the main load-bearing members of the new terminal of 1954 which replaced the old structure after it was destroyed by Allied bombing in 1944.

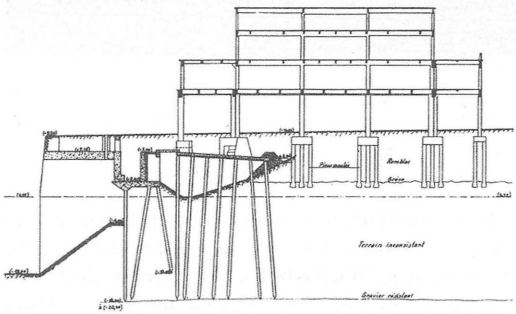


Figure 3
Cross-section through the Atlantic terminal at LeHavre.

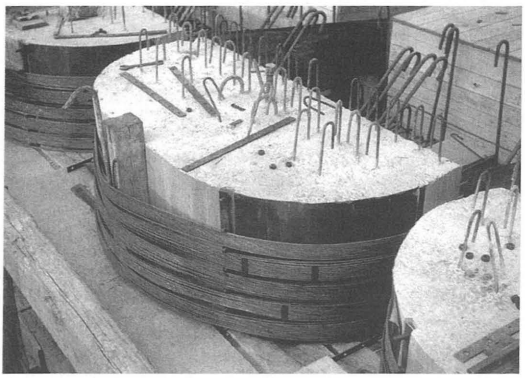


Figure 4
Prestressing system Baur-Leonhardt, similar to that conceived by Freyssinet for LeHavre: The beams were post-tensioned by means of wires looped around saddle pieces which were jacked outwards

The successful rehabilitation of the quay in LeHavre marked a breakthrough for Freyssinet. The leading engineers of his day pilgrimaged to the site — among them, Edme Campenon, who subsequently became Freyssinet's lifelong partner in the construction firm Campenon Bernard.



Figure 5
Edme Campenon (left) and Eugène Freyssinet (right)

In 1936–37, the Campenon Bernard company erected the world's first prestressed concrete bridge in Oued Fodda, Algeria, Figure 6

It consists of 4 bays with a total of 12 precast girders that span a distance of 20 metres. The bridge still stands today. The idea of prefabricating the elements was also Freyssinet's. For some time afterwards, though, there were no further contracts to follow this up.

Freyssinet's application for a patent in Germany led initially to the usual objections and formal disputes. In many quarters, his technique was regarded merely as an extension of existing ideas. No record survives of the opposition that came from Dyckerhoff & Widmann. Franz Dischinger and Ulrich Finsterwalder, on the other hand, genuinely sought a means of realizing prestressed concrete that would not conflict with Freyssinet's patent. Both engineers set their sights on reinforced concrete girders with trussed tendons on the underside.

Only one bridge was ever built to Dischinger's 1934 patent —the Adolf Hitler Bridge over the Mulde



Figure 6
The first prestressed bridge, built 1936/37, Oued Fodda (Algeria) 1999

in Aue, Saxony, in 1936–37. The steel tension chords (German steel quality St 52) were designed to allow for post-tensioning at a later date to compensate for creep and shrinkage. Post-tensioning was carried out repeatedly after 1950, but the effect always disappeared after a few years, and finally, in 1992, the bridge had to be demolished.

Ulrich Finsterwalder applied for a patent for a variation on the system of reinforced concrete girders trussed on the underside: he developed a «self-activating pretensioning» system that exploited the change of form of the girder resulting from its dead weight, Figure 7.

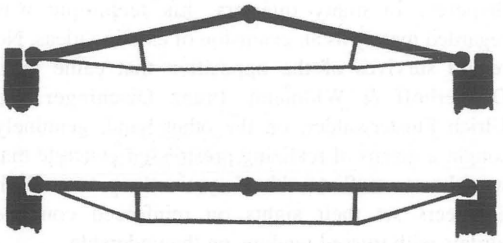


Figure 7
Finsterwalder's self-activating prestressing system.

Four structures were executed in accordance with this patent. The first was a rural road bridge over the autobahn near Wiedenbrück. The bridge had to be demolished in 1997. The well-known civil engineer Fritz Leonhardt observed of this structure that at precisely the point where the greatest bending moment occurred, there was no prestressed concrete, only a tensioned steel (St 52) tendon and a hinged joint.

The bridge was followed by the trussed girders in the roof structure over Tempelhof Airport in Berlin (1936–38) with a span of 32.5 m and steel tension chords (St 52). This completely independent interpretation of «prestressed concrete», without a hinge in the middle of the span, has been refurbished and is still in good condition today.

The roof over the «Hall of the National Community» in Weimar, built for Hitler's NS Party, consisted of identical trussed girders with a span of roughly 50 m. The building, which was completed long after the war by the East German government, is rather ugly, but still in good condition.

The same trussed girders were used for the fourth structure, the old airport in Munich, where they had a span of 80 m. The structure was demolished long ago, however.

Karl Mautner, acting on behalf of his company, Wayss & Freytag, seized the bull by the horns and entered into a licence agreement with Freyssinet in 1934. This agreement was evidently respected throughout the war and during the post-war years. In various publications, Wayss & Freytag claimed savings of 67 per cent of the normal reinforcing steel through the use of prestressed concrete according to Freyssinet's patent. That was not strictly accurate, however. What was really involved was the proportion of «permissible» stresses in the steel.

The company demonstrated the load-bearing capacity of prestressed concrete girders with two large-scale test elements. Karl Mautner was responsible for conducting these trials, but as a Jew, it was no longer possible for him to perform his role openly in Germany. He signed documents simply with his initial, «M». The results of these trials, however, were among the papers he took with him in 1939 when he fled to England.

In 1938, a first, small rural road bridge was erected with four girders, Figure 8, and a span of 32 m over the autobahn near Oelde (Beckum). The design was by Eugène Freyssinet himself, who had a mock-up girder constructed in Paris for the instruction of members of the Wayss & Freytag team. There were no drawings. Thanks to the care of the local authority responsible for this structure, the bridge near Oelde (Beckum) still stands today.

This was followed, before the war, by a quay structure and a series of precast prestressed concrete girders for factory halls that were important for the war effort. During the war years, prestressed concrete was used almost exclusively for bowstring roof girders over bunkers for the German navy. With spans of roughly 30 m, some 150,000 metres of these girders were produced in Germany, the Netherlands and Norway.

The largest structure, covering an area of roughly 5 ha (12 acres), was a submarine factory in Farge, Bremen, in which U-boats were to be built in a

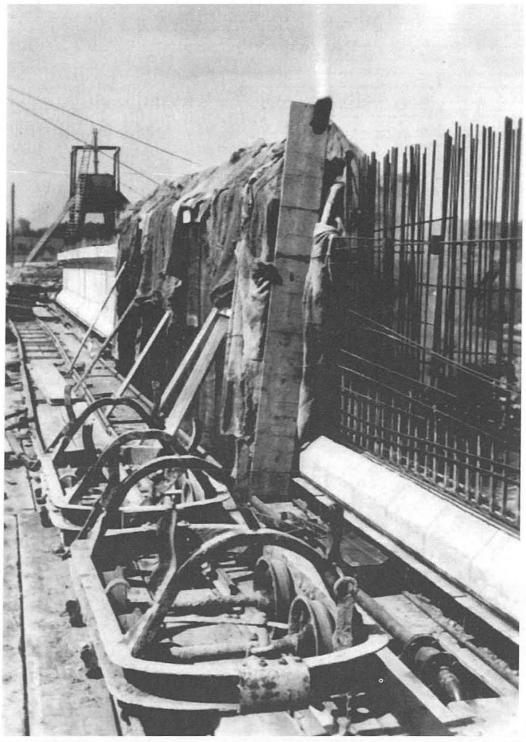


Figure 8
The girders for the bridge at Oelde (1938) were cast in sections: The rear section is complete, the central section is hooded for steam heating, and on the right only the lower flange has been cast. Lower flange prestressed with straight wires of different length, pre-tensioned and anchored on a steel prestressing bed. The stirrups were prestressed against the fresh concrete.

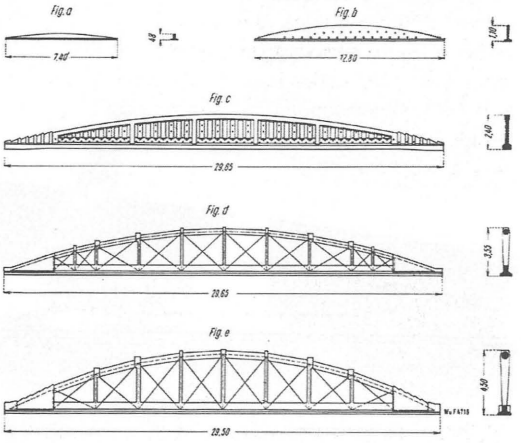


Figure 9
Types of bowstring trusses for German bunkers with straight pre-tensioned wires anchored as shown in Figure 2 on a concrete prestressing bed.

conveyor-belt system of the kind advocated by Henry Ford. Three submarines a week were to be manufactured in this way. In view of the increasing effectiveness of Allied bombs, plans were made to increase the thickness of the bunker roof from 4.5 to 7 m. The load-bearing capacity of the prestressed concrete girders was inadequate for this, however. Concrete anchorage cones invented in September 1939 by Freyssinet were therefore obtained from Campenon Bernard in Paris for additional external sheaves of prestressing wires.

In all likelihood, neither Freyssinet nor Campenon Bernard collaborated with any great zeal with the Germans. The situation was probably similar to that described by Jean Paul Sartre: «Will I be understood if I say that the occupation was intolerable, yet at the same time that we coped quite comfortably with it?»

The only three prestressed concrete bridges realized in France during the war years were not built by Campenon Bernard, but by Sainrapt & Brice, a company that collaborated closely with the Germans and that was able to divert cement and steel destined

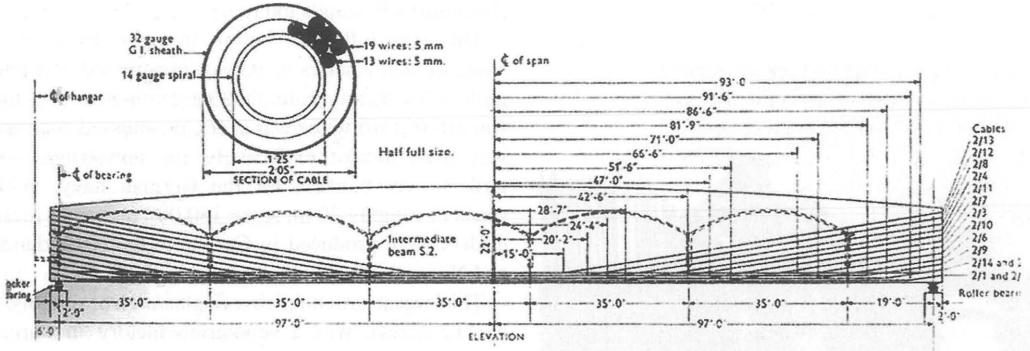




Figure 10
The hangar in Karachi, 1942 and 1998. Prestressed girders monolithic with roof shells on prestressed main beams.

for the construction of the Atlantic Wall to other purposes.

Freyssinet also took the opportunity to test his new ideas. In 1941–42, he built a bridge with a modest 10.5-metre span in slab construction over a river in Elbeuf near Rouen. It is the first post-tensioned cast in-situ bridge. He used his new system of sheaves of prestressing wires with concrete anchorage cones being no longer straight but curved and coated with bitumen to avoid bonding. In addition there were straight transverse tendons of the same kind. In 1942–43, a similar slab bridge with a 20-metre span was built over a river in Longroy near Eu-le-Tréport. On this occasion, post-tensioning was applied step-by-step. Between 1942 and 1944, a precast footbridge with spans of 30 and 31 m was constructed over the railway line near Lens. None of these three bridges was a crucial transport structure or of any significance for the German occupying powers.

In that respect, the first railway bridge in prestressed concrete was presumably a different matter altogether. It was built in 1943–44 over the rue Miroir in Brussels by Gustave Magnel in collaboration with the construction company Blaton-Aubert and still exists today. The bridge was certainly of interest to the German military. In this structure, Magnel tested new, and again curved, multi-wire tendons in flexible rectangular ducts, since he was not entirely satisfied with Freyssinet's solution. At that time Magnel had no contact with the latter, however.

Meanwhile, far removed from Europe, Robert Shama, an Egyptian who had studied in France, used Freyssinet's new tendons in spectacular form in a military aircraft hangar built in Meerut north of Delhi. Erected in 1940–41, it was probably the first cast in-situ structure to be realized with curved tendons, even before the bridge at Elbeuf. The tendons passed through flexible sheathings and were anchored by means of those concrete anchorage cones invented only in 1939. Although C. G. Sexton announced this building as if it were his own, Sir Alan Harris believed Robert Shama to be the true author of the scheme. The construction firm was J. C. Gammon. According to information from the Aeronautical Information Service, Delhi, the hangar has since been demolished, but a similar structure dating from 1942–43 in Karachi still exists and appears to be in a good state, Figure 10.

In Germany, it was probably not possible to use curved prestressing, since Freyssinet's German patent specified the use of straight prestressing reinforcement.

Between the construction of the many bunkers, a single structure for civilian use was erected: an autobahn bridge consisting of precast elements and spanning a distance of 42 m across the river Klodzka Nysa. The bridge was built in 1940–41 east of Breslau (present day Wroclaw in Poland) and is still in an excellent state of preservation (1998).

After the war, Freyssinet referred to the two German bridges as «*assez mal*», although at least one of them was directly designed by him and the other one complies with his concept for the first bridge. The way he dissociated himself from these objects is perhaps understandable, though, seen in the context of the times.

As described earlier, Karl Mautner had fled to London in the summer of 1939 with the results of the German and French trials in his luggage. In contrast to the reception given to prestressed concrete in Germany, it was the subject of an open debate at the Society of British Civil Engineers in England. As early as 28 May 1940, a trial girder was tested to failure. Parallel to this, in 1940–41, what was the largest bomb depot in the world at that time was constructed in an underground quarry, using some 3,000 prestressed concrete girders with a span of 5 m.

In England, as in Germany, Freyssinet's 1929 patent was used solely with straight prestressing wires directly bonded to the concrete. Only in trial forms of construction were precast segments assembled with curved post-tensioned tendons.

This segmental form of construction —based on Freyssinet's ideas— was first used in 1944 in a bridge in Djedeïda near Tunis. The 75-metre-long bridge across the Medjerda Wadi has a 50-metre central span and was built with 3-metre precast segments by Campenon Bernard without the direct collaboration of Freyssinet. It was constructed because the Allied armies urgently needed a reliable line of access to Ferryville (now Menzel-Bourghiba), where the largest dry dock in the region was situated. The bridge still stands today, but it has been strengthened in the middle bay with two auxiliary transverse beams supported by piers.

In the public debates about prestressed concrete construction held at the Society of British Civil Engineers, Paul Abeles, an emigrant from Vienna,

disagreed with Freyssinet and Mautner, who insisted that the concrete should be free of cracks. Abeles claimed that this was not necessary and that a further 20 to 30 per cent saving in the quantity of steel could be made if cracks were tolerated in the concrete. According to the extensive investigations he had carried out, there was no danger of corrosion with cracks of limited width, he argued. Paul Abeles may therefore be regarded as the inventor of the questionable technique of partial prestressing.

Without doubt, the man who had the greatest commercial success with prestressed concrete prior to 1945 was Ewald Hoyer, who developed a system for small prestressed and pre-tensioned beams with very thin hard-drawn wires which he named «piano-string-concrete». The beams could be cut to any length required, since the wires expand elastically at the cut and re-anchor themselves instead of losing their tension. This principle had already been described in a French supplementary patent for which Freyssinet had applied. Hoyer was nevertheless granted a German patent as a result of special wartime legislation, and in Gennevilliers near Paris, he manufactured incredible quantities of beams for bunkers in the German Atlantic Wall. As many as 1,500 people worked in the Gennevilliers plant, and the occupying powers forced Campenon Bernard to place a number of its engineers at the disposal of this works. The thought that Hoyer's German patent was not legally valid in France was something no one dared to express.

After a tremendous boom in the post-war years, the history of prestressed concrete —at least that with embedded tendons— is now coming to an end. Paul Abeles was, unfortunately, mistaken in the pronouncement he made in London in 1940. Prestressing steel does corrode through cracking of the concrete and even without cracks.

The close economic cooperation between France and Germany as one knows it today had its origins in the years between the two World Wars and continued —albeit in a different form— during the German occupation of France. In the post-war years, this cooperation led to the creation of the European Coal and Steel Community (ECSC) and ultimately, by way of the EEC, to the present European Union.

As this brief history of prestressed concrete shows, these developments were closely parallelled in the building sector, where early international links were forged between France, Germany and the UK. One sees, therefore, that some of the seeds of modern European cooperation were sown during the darkest years of the 20th century.

Perhaps one may end this story on a more conciliatory note. The painter Emil Nolde, who fell out of favour with the Nazis for his «degenerate art», was ultimately no longer able to purchase paint. Quite by chance, his friend Max Lütze was responsible at Wayss & Freytag for maintaining contacts with Freyssinet, and on those occasions when Lütze visited Paris, he brought back paint for Nolde. His paintings belong to the most beautiful things that ever came of prestressed concrete.

[English version by Peter Green]

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Foundries and metallic architectonic elements manufacture of the 19th century in Recife (Brazil)

Paulo Martin Souto Maior

Economic renaissance and strategic position

With the reduction of gold reservations especially alluvium in the province of Minas Gerais, the activity rendering high benefits to the metropolis was agriculture especially sugarcane. The economy of Pernambuco stifled by the precious stones, diamonds and gold of the Brazilian Southeast recovered, in the second half of the 18th and in the beginning of the 19th, century the economic prestige of the older day was recovered as well. In those years, exports resumed their growth and the ascension continued up to 1890.[1] The French revolution contributed to this economic renaissance as well as the colonies producing tropical commodities. Later on, with the Napoleonic wars, the European blockade and the disarticulation of the vast Spanish empire in America provided Pernambuco with great economic advantage.[2] The recovery of that province was so outstanding that in 1812 sugar production already surpassed that of the beginning of the 18th century.[3]

However, the situation of Brazilian rural sugar producing provinces, among them Pernambuco, was not to last long. With the end of the Napoleonic wars and the European political stabilization sugar production in the Antilles and in India was recommenced. As a result, the product suffered continuous devaluations in the international market. In addition the Western Indies forced by the 1834 Act to employ free men in their sugar plantations, would seek protection from the British Government. To meet the requests of English planters in 1842 Great Britain heavily taxed the sugar producing countries using slave labor and that directly affected Brazil.[4] Another contributing factor was the thriving beet sugar industry, especially in France, causing many problems to the economy in Pernambuco, for to compensate the scarcity of the colonial sugar due to the Napoleonic blockage Europe had been developing beet sugar since the beginning of the 19th century. The situation got worse following the war when the industry received governmental protection and established itself as the principal competitor of sugarcane sugar.[5] The numbers are revealing for the value of the ton of sugar, which was of 24 gold pounds per ton from 1821–1839 in 1831–1840 dropped to 16,8, or, approximately seven pounds less per ton.[6] Therefore, when considering the region's sugar hegemony in the international market lasted only the period of European conflict, it was still sufficient to settle the basis of the slow industrialization process beginning in the second half of the 19th century.

The opening of national ports to the foreign markets in 1808 compounded on these political and economic events. From that date on agricultural equipment, foundries, and mechanic shops began to open in Recife. In the beginning, they did maintenance work. Afterwards they manufactured always copying imported products, balconies, gates, grates, mensules, beams and even steam engines. Thus, an environment was created in which the expertise of working metals began to gradually grow not only in the capital but

also in some of the cities in the interior. At that time there was a Society for the Support of the Art in Iron[7] founded in 1881 comprised of metalworkers, forgers, blacksmiths and tinkers producing furniture, grates and doing equipment repair, specially agricultural ones as well as small services, the ones that did not interest the larger foundries.

Therefore, the economic surge had an outstanding role in the introduction and replacement of technology in the province. However, all became possible specially due to the fact that the city was located more to the East of South America being an almost mandatory port for the routes to the West of the South Atlantic. In addition, the port comparable to the Port of Recife, in the mid 19th century, the port of Salvador, occupied that position but its proximity to Rio de Janeiro eventually deviated many of the commercial routes directly into the capital of the country.

Table 1. Movement of the Ports of Recife, Salvador and Rio de Janeiro in 1866[8]

	Rio de Janeiro	Recife	Salvador
Ships	4506	3173	1707
Direct foreign imports	73.844:227$000	22.221:299$000	17.878:203$000
Travellers	57122	39353	31915

Foundries and mechanic shops

The fifteen existent metal foundries in Recife, in the middle of the 19th century and beginning of the 20th century were identified especially through newspaper ads. It was perceived throughout the research that there were two marked differences in the profiles of these Companies. The majority of them attempted competing with imported products specially in furnishing sugar mills parts and the remainder, on the other hand, acted as importing agents.

In the first profile one could include Starr & Cia, Caldeiraria Nacional,[9] Fundição de Francisco Antônio Correia Cardoso,[10] Fundição Villaça,[11] Grande Caldeiraria de Domingos Ferreira & Cia,[12] Fábrica and Fundição de Bronce de Braga & Sampáio,[13] Caldeiraria e Fundição de Bronze de José Laroca & Cia,[14] Fundição Santa Rita,[15] Oficina Mecânica de Simplício José de Melo,[16] Caldeiraria Central de Eduardo de Mesquita Cardoso[17] and Andrade & Leal.[18] Among them, the first one presents in addition to the adds in the newspaper, filed documents with installation descriptions and production which X-rays and indicates in what circumstances foundries were assembled in a city that did not possess the raw materials nor tradition in the trade.

Its founder the Englishman Cristopher Starr, came to Recife in January 12, 1820. He was 44 years old at the time and in the beginning he dedicated himself to the maintenance of the almost inexistent manufacturing plants in Pernambuco, specially of «machinery dedicated to the preparation of cotton».[19] He perceived in this activity, influenced by the industrial thinking of his country that the cotton planted in the province could be manufactured prior to exportation. Therefore, he assembled a cotton manufacturing plant in 1820 in the village of Limoeiro but the business did not produced the desired results for «the principal motive for the plant abandonment was the impossibility to gather sufficient cotton to keep the plant in constant operation».[20] But in 1829 he decided for another larger and more ambitious venture, to assemble a small foundry in Recife. This way one of the most important metal manufacturing plants began in Recife in the 19th century.

The oldest physical description that could be analyzed is an entry in the diary of D. Pedro II during his visit to the city in 1859. At that time, approximately 60 people worked there and in only five years the number had almost doubled. These were «Englishmen, Portuguese, Germans and locals totaling 110».[21] The Englishman work rhythm was rigorous. He would open at six in the morning and following a small pause of half an hour for lunch he would close at six in the afternoon. His foundry in 1859 had seventeen furnaces, of which the three largest ones were to smelt iron and the remaining were for the forgeries. In addition there was a die

shop, where maybe the once lost wax technology was applied for a record of 1860 depicts that «the national ship Itaberá, landing in Rio de Janeiro», brought «wax, 2 boxes for Cristopher Starr».[22]

Also located in the Public Archive of Pernambuco, the blueprint of the foundry of 1864. Part of the terrain's dimension of approximately 13.000 m^2, the information pertaining to it is scarce but the list with over thirty equipment serve as a basis to imagine that this was one of the largest manufacturing facilities in Recife in the 19th century. Among the various existing equipment there were two 14 inch dies, a torque machine, a plane machine, two boring machines, a steam fueled hammer, two steam motors for joint or separate operation, a ventilator for the blacksmiths, a mill to produce charcoal powder, a ventilator for the furnaces, a large chimney, a tubular boiler, two hothouses, a furnace to smelt iron, nine iron gantries, a hand oven and 3 smelting furnaces for blacksmiths.[23] At the time it could be considered an industry for the word meant «art, ability to make a living, mill, the art of chiseling, to do mechanical work».[24] Thus to invent, create and build was equivalent to industrialize.

In the face of this industrial trait and pioneer of the foundry, on the other hand there were two obstacles for the industry in Recife, especially the ones doing metalwork. One of them was the importation taxes for raw materials and the other the competition of European manufactured products for agriculture which in 1857 were taxed a mere 5%. In relation to the first one the foundries owners could do nothing. The fault lied in Government and its lack of interest. Two facts that occurred with Starr illustrate this lack of protection very well. Since 1830, he had requested tax exemption to import iron but only got it three decades later. Even then, quantity restrictions were made for he could only import sufficient supplies for one year. For this reason, in the following year, he again attempted but this time «1.800 tons of casted iron in rough ingots, 240 laminated and 100 bars and rods». A quantity, thought Starr to be smelted during a long period, but unfortunately even if his Company was considered a National Plant by Decree 526 of July 1847, the request was denied. Another fact happened when he was traveling to the United States and England to «hire workers. But in the course of such diligent task he heard there would be considerable change in the Customs Tax System which obliged him to stop all hiring proceedings».[25] Because of these and other facts, he regretted to confess, «in such circumstances it's almost impossible to go on manufacturing anything of the kind [?] or even to exist for a long time in the country».[26] This lack of protection with the Brazilian manufacturing plants was criticized by the province's president himself who stated that «trade shrinks, for instead of protecting and supporting the government of this country has offered complete indifference and abandon compounded with inconvenient and unfeeling rigor».[27]

In 1850, two circumstances marked the history of the foundry. The news of the death of Cristopher Starr's wife, Susana Star, in 1853[28] and, two years after, a severe accident when «without any reason the boiler exploded and in the attempt to save the victims three dead men and four lightly wounded ones were removed and two severely burnt by the boiler's water».[29] The following decade marked the end of the foundry. Starr was then 80 years old and attempted for the last time to obtain some profit from the facilities of his Company. He pleaded for help from the Emperor «he would cede his establishment to the Imperial Government for a reasonable financial compensation, with all the shops, buildings, land and warehouses for the establishment of the War Arsenal of the Province»[30] This would be, according to him, a great opportunity for the government. He argued in a patriotic way and taking advantage of the fact that Brazil was at war with Uruguay and Paraguay that the location was ideal «to receive the War Arsenal not only because it has sufficient rooms for the various activities of the Organization, but because of all of the machinery and adequate tools to manufacture all types of blade weapons, fire weapons and any other devices required to a War Arsenal. Brazil will not need to procure the weapons it needs for its army, navy and fortress from foreign countries; we currently have the imperious need of manufacturing them in the country and we do not have to procure these indispensable objects for the practice of military science abroad, for they are needed for the protection of any State».[31] The major advantage would evidently be his for he would be compensated for a Company in dire economic difficulties.

His proposal was not accepted and in 1870 the obituary in the Diário de Pernambuco, announced that «from the last ship coming from Europe there's news that Mr. Christopher Starr am English subject and owner of a major iron foundry called Aurora located

in Santo Amaro, has passed away, he was the owner of the first industry of its kind in the Province».[32] Three years later the foundry was put to sale but as no buyer was found, it was auctioned.

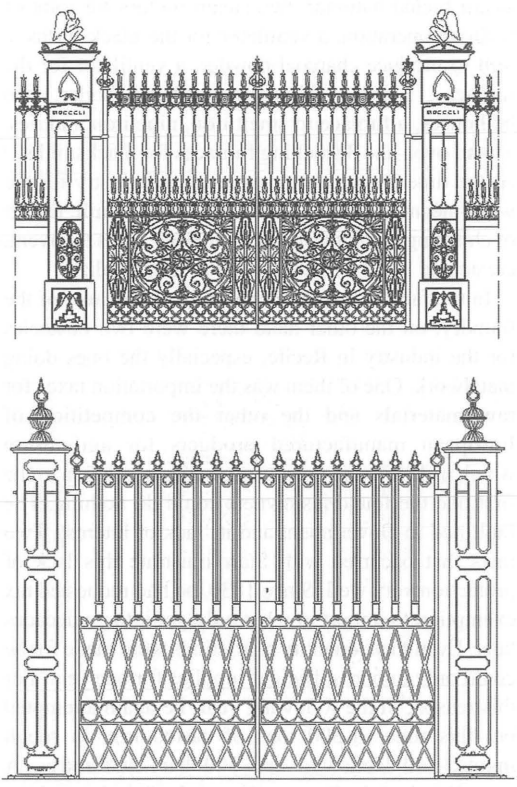
The Foundry building was described at the auction announcement. At the definite closing of its activities the building had «iron beams and thresholds. Five rooms, seven bedrooms, kitchen, a roofed terrace with a magnificent view, yard and garden. The rooms in front can be reverted into a great salon for the compartment dividing them is movable, there's a pipe system for water and gas, bathroom and fences around the yard with greenhouses and many trees».[33]

A frequent trait of Starr was to state that he manufactured all that he sold. In 1848, for example, with some typical advertisement newspaper exaggeration, he bragged that had «the most modern and complete machinery that science introducing, comparable ... and selected among the best in Europe, truly able to offer sugar mill owners all possible credibility».[34] Years later, like in 1851, the same emphasis: «since the beginning in of 1829 it has constantly increased and has currently achieved such perfection that it is not inferior to the best available».[35]

That means that, it did not only compete with domestic foundries but with foreign ones too, and in this aspect Bowman, as we will see later, in addition to other establishments, was more coherent. Maybe Starr refused to give up and realize that competing with foreign foundries due to the legislation of that time and the material and technical dependency was an almost impossible task. The fact is that few foundries in Recife were aware of this situation, and when perceiving the lack of governmental interest, had no other choice but to act as commercial agents as well. The owner of perhaps the biggest of them all did not do this and that is the reason why, following his death the remains of his company had to be auctioned.

Among his products, the one that is most outstanding and far ahead of other foundries in Recife, is that Starr is said to have built the first steam engine in Brazil for the Caraúna de Souza Leão sugar mill. At the time of the Emperor's visit approximately fifteen of them had been sold to other sugar mills of the region and not only in the 1864 document, as well as in the diary of Pedro II and in newspapers adds there are references to his pioneer endeavors. In addition to this, a hydraulic bell was casted for the Arsenal of the Navy for it weighed around seven tons and there was space to build two medium sized ships for there was a channel of the river flowing into the plant itself through which ships navigated. Pedro II registered that he had seen an iron boat, possibly used to move merchandise.[36] These are amazing facts for a rural region in 1859 and contrasting with the policy, or lack of it, adopted by the government and related to national manufacturing plants, specially the ones in Northeast Brazil.

In terms of architecture he announced that he could build «iron bridges of all dimensions, grates,



Figures 1a and 1b
Two gates models of the Star foundry in the city. The one in the left was at Ruy Barbosa Avenue nº 1229 and 1426, at the Hospício nº 51, at the cemetery of Olinda, in the cemetery of the Englishmen, and at the Caxangá avenue nº 3860. The left one and example of exquisite workmanship and decorative elements in forged iron in the cemetery of Santo Amaro and in the Church of the Ordem 3ª de Nª Sª do Carmo in Recife

verandas, gates, columns, (. . .)» and almost all classes of metal structures. As for example the cases of the Brunzinho and Varadouro bridges.[37] However, unfortunately, a few samples of the Starr products still remain and there are, nevertheless, some gates in the city. Among those the ones in the Ruy Barbosa Avenue nº 1229 and nº 1426, at the Hospício street nº 51, in the cemetery of Olinda dated 1858, of the cemetery of the English dated 1814[38] and in the Caxangá avenue nº 3.860. In addition to other two of the cemetery of Santo Amaro dated 1851 and of the Church of Ordem 3ª de N. Sra. do Carmo dated 1858, are outstanding in terms of exquisite finish and ornamental elements (Figures 1, 2, 3 and 4).

Still focusing the profile of the foundries that «compete with the plants in Europe in quality and workmanship»,[39] in one of the ads of Andrade & Leal —Fábrica de Caldeiraria, there were— typical products such as alembics, tacks, tin furniture, iron carts, gates verandas and gratings[40] —an illustration

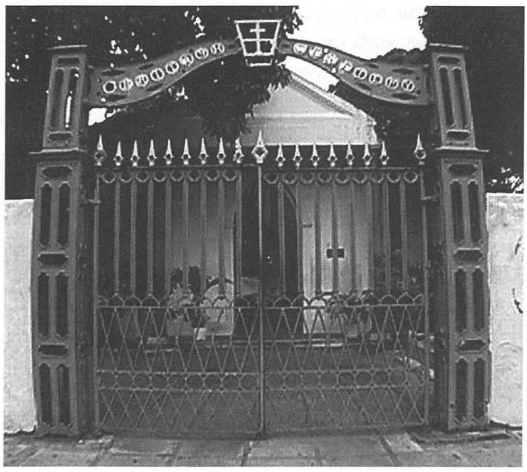


Figure 3
Gate of the Englishmen Cemetery



Figure 2
Detail in forged iron of the main gate of the Santo Amaro cemetery



Figure 4
Gate of the nº 1426 house at the Ruy Barbosa Avenue

depicting the technique used at the time. These are workers that with the manufactured caldrons such as the ones used in the sugar mills (Figure 5).

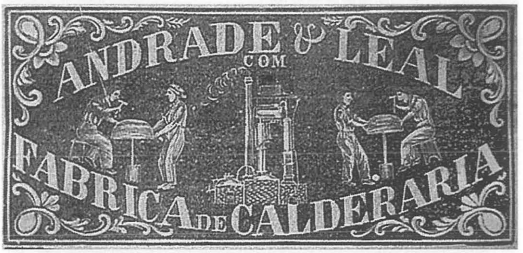


Figure 5
Ad of the Fundição Andrade & Leal-Fábrica de Caldeiraria (June 2, 1851. *Diário de Pernambuco*. APEP)

The Grande Fábrica de Caldeirarias and Fundição de Sinos Villaça (Boiler and Bells Plants) placing ads in the newspapers up to 1905,[41] also used illustrations (Figure 6). Iconographic materials enable the identification of the same technique employed by Andrade & Leal. These workers and slaves produced boilers, alembics, tacks and even copper pumps.[42] The ad is a reference to the delay of some of the foundries or stated they were not much different of the ones in France one century before, as an example of the ones appearing in the *L'art du Serrurier* de 1767.[43]



Figure 6
Ad of the Fundição Villaça (August 12, 1872. *Jornal do Recife*. APEP)

The second profile, or the foundries that got into importation, and in some of the cases represented foreign companies, belonged to companies such as Cardoso & Irmãos,[44] Fundição Geral and Oficina de Samuel Power Johnston & C[45] and Bowman. Especially the last one, like Starr, due to the documentation on file and because some of the products still exist, mostly architectural ones, reflect with greater detail the peculiarities of this type of activity in the city.

The sources consulted indicate two dates for the Bowman foundry foundation. One of them is a booklet of the foundry itself, printed in 1855, from which one is able to infer that it existed since 1844.[46] But, in the diary of Pedro II, the date of 1835 is indicated as the date the company opened for business in the city.[47] Apart from the discrepancy of one decade, the brochure depicts with a certain amount of detail, its technical level. The establishment occupied a terrain of 3.000 m^2 and, according to Bowman, he employed approximately «60 officers, every one of them Brazilian».[48] His infrastructure was comprised of two main cranes, in addition to other five cranes that ran on three ways. The mechanical force was obtained through a six horsepower steam engine operating three lathes with the ability to fold almost 2,5 m wide parts. In addition there were machinery to smooth, perforate, screw, forge and cast iron, as well as grindstones and bellows for furnaces and forges. The sixty workers were provided with two furnaces for iron and two furnaces for bronze. The largest was capable of producing 1.350 kg per hour and, according to Bowman, the monthly production at that time was of approximately 20 tons.[49]

This was a middle-sized foundry and could be considered with Starr as the first pre-industrial establishments in Pernambuco. But, the data when confronted with that of European companies such as, the *Siderurgie en France & à L'Étranger*,[50] indicated that the two represented only small mechanical shops capable of melting iron for balconies, grates, to furnish parts and maintenance to the sugar mill plants. However, the issue is that we are talking about a country that, three decades before was still a colony of Portugal, and therefore in this context a true pioneer spirit prevailed.

At the time, the State desired to facilitate the acquisition of machinery for agriculture as well as to replace primitive processes principally concerning

sugarcane and cotton. But, on the other hand the sugarcane owners would then cease buying their products from locals and would directly import from the European foundries. The more complexity mechanisms unavoidable were imported but, parts and replacement materials, such as tacks, plaques, beams, tubes could be manufactured in Recife. If taxes were to be cut, then why not buy directly from the European manufacturers? Therefore, for manufacturing plants, principally mechanical shops and foundries, the measure would result in severe negative consequences. The region needed to become technically modern such as the government proposed to, but this implied in sacrificing the few manufacturing plants existing in Recife. The problem was not easily solved and Bowman as well as other foundry owners feared for the future of their business for they thought that «if in fact taxes on imported machinery are cut it will become absolutely impossible to have them manufactured in the country because of the price competition with the imported ones and in consequence I will not have other alternative but to layoff my employees and close my business».[51]

Bowman, as well as Starr, also began manufacturing steam engines. At the end of the 1850's, he had already built «three steam engines and mills and implements such as 6 horsepower for mills».[52] Even such initiatives like that were blocked by technical superiority of the foreign manufactured products. That is why some sugar mill owners, even when having to pay more would rather order directly from European manufacturers. The reason was that «the products of the Starr foundry were not good and, Bowman was too expensive: I have sent for the main parts from Europe» one of them confessed to Pedro II. Another sugar mill owner stated that «Starr's low price results according to Lourenço de Sá e Albuquerque, in the bad quality of the products, Bowman's products are better according to what Boa Vista said».[53] And this could not be different. These were the first metalworkers of the city and the intention of competing with the English, French and Belgians was a challenge to be admired.

In 1857, Bowman's fears were confirmed. The taxes of 30 to 35% excised from agricultural machinery since 1844, from Alves Branco importation tax, was reduced to a 5% tax on all equipment. From then one the disadvantages of the local foundries in relation to the foreign ones increased. To compound the negative situation, there was a local Provincial Regulation number 211 dated from 1852 that extended the benefit of the tax exemption awarded to Alfredo and Eduardo Morney in 1849 to all imported agricultural implements.[54]

Because Bowman's advices had no standing and importation taxes were in reality reduced, in the face of this new competitive and unequal context the only thing left was to plea at a local level. Therefore, through four pleas the taxes charged to the local industries were contested. Of the four petitions, the three first ones were denied and probably the same happened to the forth. The texts and contents are similar, but the third one in particular the part of the text describing the critical state of the city's foundries due to the policy adopted by the government is outstanding:

> there are in this city four iron foundries, and only three actually operates having reduced the number of workers, and the one in the Aurora street is closed because no one is willing to rent it, although it is well assembled. There are houses at the Rua B. Do Triunfo closed with no one willing to rent them which were formerly ironsmiths, metalworkers and boiler manufacturers shops.[55]

However if the foundries, according to Bowman, were in difficulty, how can one explain the increase of manufacturing ads in the newspapers starting exactly during that period? In reality, although governmental measures had on one side wiped the first foundries of Recife, on the other hand, it encouraged the importation of machinery, and as a result, the emerging foundries offered basic parts and mills maintenance services to sugar mill owners, their main clientele. That's what happened to Bowman and perhaps that was the only way his company was able to survive. In that way the initial position like in the first 1848 ads is similar to Starr's when he stated he could produce «as perfectly as the best plants in England and much superior to the ones generally imported from that country»[56] had changed. Afterward because of the competition and not being able to resist for long, he began to represent foreign companies, or to become an ally of his former competitors. In addition to the foundry, he then became an importer and commercial agent. An ad, published in the Jornal do Recife in 1878 highlights the following: «for the orders of vacuum boilers, devices for sugarcane juice cleaning, evaporations or

steam cooking etc. This foundry has the best offers due to its relationship with the main manufacturers of England, France and Belgium». Besides profiting with the commission, the same ad enables one to note that the Company would maintain its principal activity for it would «contract for the supply, training on the job of any machinery, all together or one by one, furnishing the original accounts and patents for the appreciation of the buyer».[57]

Bowman's ads are frequent throughout the whole half of the 19th and the 20th century. There three phases in the business. The first as a mechanical shop specially producing «a great variety of caldrons for sugar mill, of all sizes and models, the most modern and approved. In the same plant we accept orders for steam engines, water wheels, spiked wheels and all other machine parts, with perfection and reasonable price».[58] Two decades later he began to represent European companies, specially English ones for they «will remit at the order of clients, reminding them of the convenience of doing their shopping through someone who knows the equipment well and is able to render assistance in case of need».[59] At last, in the ads of the beginning of the 20th century, also advertised construction services «of bridges, buildings, orders for machinery and assembly for any plant, assuring excellent manufacturing results».[60]

Of the six decades of existence, one of the longest among the city's foundries, only the gate of the old Detention House remains to document the products of that company. Although there are no inscriptions proving where it was forged, there are strong indications that it must have been built by Bowman. One of them in the Diário de Pernambuco, in the Official Part in March 2, 1855 indicates that the Treasury inspector of that time authorized that «the Director of Public Constructions should contract with David W. Bowman & Cia. The bill of such construction for 240 rs. for each pound of gate and 200 rs. for the large lateral grates».[61] In addition to this it should be considered that the metalwork of the Detention House was ordered as the building was being constructed, or gradually and not like when metal elements were imported from Europe and would come all in one shipment.[62]

In this context possibly the same thing occurred with some of the metal parts of the interior of the building. There is in the State Public Archives a drawing, regretfully in very bad conditions, of the mensules details made of forged iron supporting the circulation area of the pavilions. In the first place it should be considered that the plans related to the imported metal structures were designed primarily for parts assembly and, many times, did not discriminate each of the elements but their connections, in short they was utilized like a guide to assemble. At last, because Bowman was hired to furnish gates and lateral gratings and, together with Starr & Cia, were at the time the largest foundries in the city with sufficient technical expertise to produce such parts, at least if there is no proof in which foundry they were manufactured, it's possible at least to think they were forged in Recife (Figures 7, 8, 9, 10 and 11).

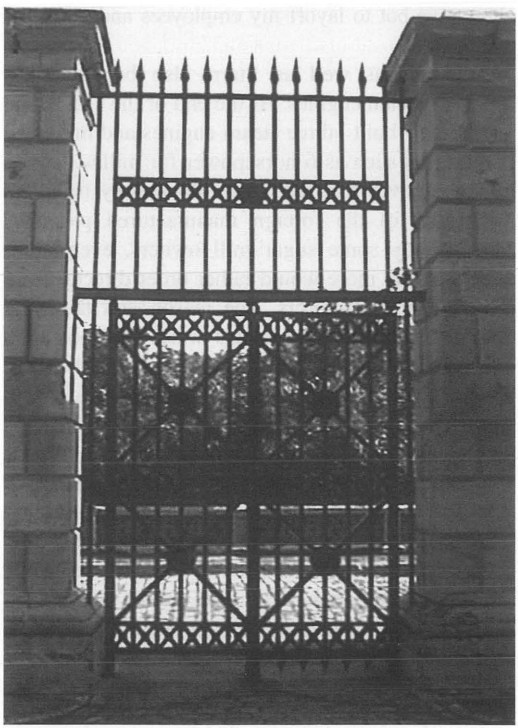
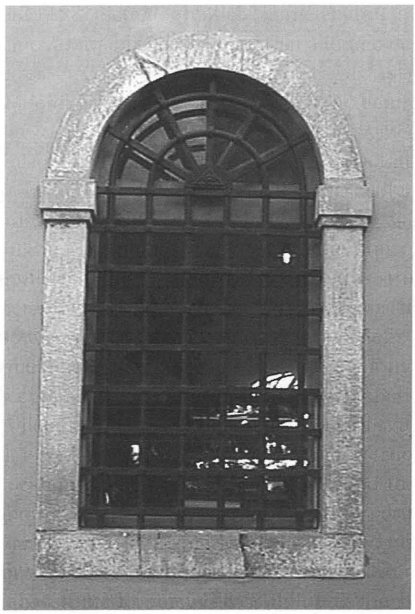
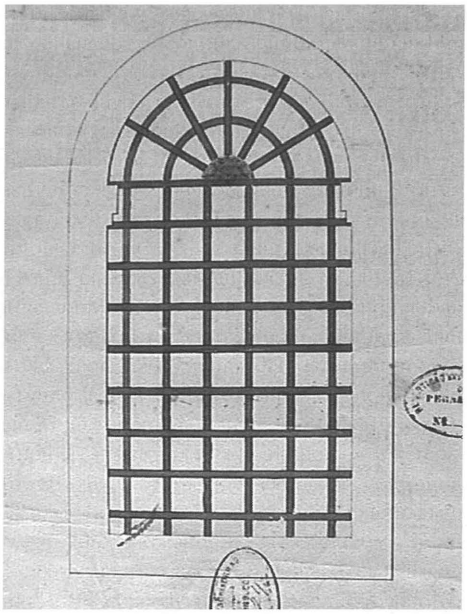
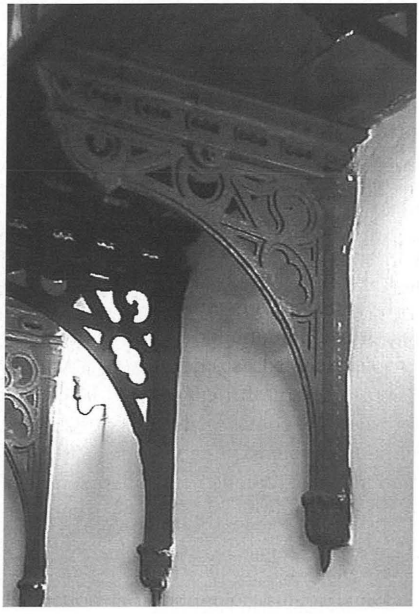


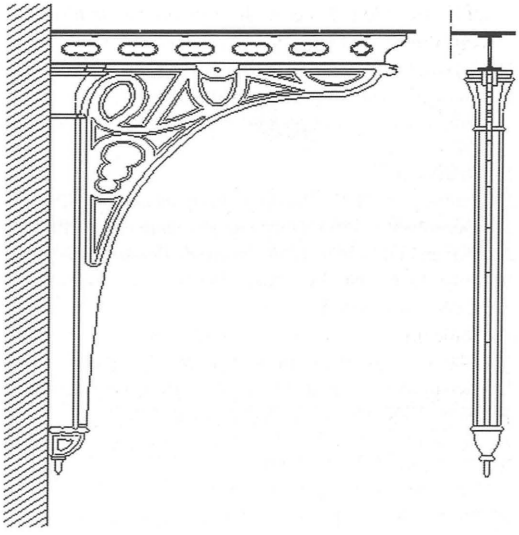
Figure 7
Iron gate of the old Detention House in Recife manufactured by Bowman foundry





Figures 8 and 9
Window and drawing of the grates of the old Detention House of Recife, possibly produced by the Bowman foundry Bowman (APEP 1852)





Figures 10 and 11
Mensule of the Old Detention House forged in Recife

Notes

1. Eisenberg 1977, 77.
2. Furtado 1980, 92.
3. Lima 1976, 221.
4. Wright 1978, 18.
5. Eisenberg 1977, 45.
6. Lima 1976, 199.
7. August 19, 1881. Section: Revista Diária. In *Diário de Pernambuco*.
8. Pereira. 1972. *Notícia dos principais portos do Brasil e dos gêneros que por eles saem*. In *COIMBRA*. 72–76.
9. May 9, 1890. Diário de Pernambuco. Arquivo Público Estadual de Pernambuco. (APEP)
10. May 2, 1868. *Diário de Pernambuco*. APEP
11. May 9, 1905. *Jornal do Recife*. APEP
12. July 4, 1894. *Jornal do Recife*. APEP
13. September 19, 1863. *Jornal do Recife*. APEP
14. February 23, 1894. *Jornal do Recife*. APEP
15. August 15, 1906. *Jornal do Recife*. APEP
16. March 21, 1896. *Jornal do Recife*. APEP
17. May 19, 1875. *Diário de Pernambuco*. APEP
18. June 2, 1851. *Diário de Pernambuco*. APEP
19. July 13, 1864. *Petições de Indústrias e Comércios*. 3. APEP
20. July 2, 1856. *Diário de Pernambuco*. APEP
21. July 18, 1864. *Petições de Industrias e Comércios*. 3. APEP
22. Diário de Pernambuco, August 2, 1860, Comercial Section —Movimento do porto— Importação.
23. July 18, 1864. Nota A. In *Petições de Indústrias e Comércios*. APEP
24. Silva 1818. Instituto Arqueológico, Histórico e Geográfico de Pernambuco (IAHGP).
25. July 18, 1864. *Petições de Indústrias e Comércios*. 4. APEP
26. Ibídem, 3–4.
27. January 15, 1875. *Diário de Pernambuco*. APEP
28. December 3, 1853. *Diário de Pernambuco*. APEP
29. November 8 and 9, 1854. *Diário de Pernambuco*. APEP
30. July 5, 6 and 18, 1864. *Petições de Indústrias e Comércios*. APEP
31. Ibídem.
32. March 30, 1870. *Diário de Pernambuco*. APEP
33. September 23, 1851. *Diário de Pernambuco*. APEP
34. May, 1847. *Diário de Pernambuco*. APEP
35. September 23, 1851. *Diário de Pernambuco*. APEP
36. D. Pedro II 1859, 69–70.
37. 1858. *Relatório de Obras Públicas*. 13–17.
38. The date 1814 (MDCCCXIV) that could be still observed in that gate is a mistake because Starr arrive in Recife in 1820.
39. June 2, de 1851. *Diário de Pernambuco*. APEP
40. Ibídem.
41. May 9, 1905. *Jornal do Recife*. APEP
42. July 2, 1879. *Jornal do Recife*. APEP
43. Duhamel, M. *L'art du Serrurier* In: Carria 1995, 29.
44. March 17, 1863. *Jornal do Recife*. APEP
45. July 9, 1872. *Jornal do Recife*. APEP
46. Folhetos Raros III, 400/900, cx. 29/0059. APEP/PE
47. D. Pedro II 1859, 74.
48. Folhetos Raros III, 400/900, n. 59/cx. 29, fl, 1. APEP/PE
49. Ibídem.
50. Helson 1891.
51. Folhetos Raros III, 400/900, n. 59/cx. 29, 2. APEP/PE
52. The significant different related to booklet dated 1855 relates to the capacity of the main furnace that from 1350 Kg /h in 1855 to 2t/h in 1859. The rest of the equipment suggests that few changes in the years between the two sources were effected D. Pedro II 1859, 74.
53. Ibídem 1859, 74–128.
54. Coleção de Leis do Império do Brasil de 1852. 15: 213. 8a caderno. APEP
55. 29 April 1875. *Petições de Indústrias e Comércio*. 30–38. APEP
56. November 22, 1848. *Diário de Pernambuco*. APEP
57. January 31, 1878. *Jornal do Recife*. APEP
58. November 22, 1848. *Diário de Pernambuco*. APEP
59. January 3, 1869. *Jornal do Recife*. APEP
60. February 27, 1907. *Jornal do Recife*. APEP
61. March 2, 1855. Official section. In *Diário de Pernambuco*. APEP
62. APEP-R.O.P 1853, 3–8; R.O.P 1854, 14–25; R.O.P 1855, 33–34; R.O.P 1858, 12.

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Technical literature from the Enlightenment to the Portland cement era: Its contribution to the knowledge of masonry buildings and the History of Construction

João Mascarenhas Mateus

Knowledge of the construction of historical masonry buildings is fundamental to their study and to any decision making in their conservation and restoration. Masonry technology is in turn indispensable to any discussion of the history of construction.

A fundamental source of information about masonry techniques can be found in the technical literature published during a particular «golden» historical period, from the mid eighteenth century to the close of the nineteenth century. This period is characterized by the collection, the classification and the availability of centuries of knowledge about building practices in written form. In this period, this knowledge became the object of widespread study and of scientific elaboration, which led to the theorisation, the standardisation, and the optimisation of traditional methods and materials. Also in this period, new modern standards of materials and processes started to emerge and to replace traditional ones. The beginning of this period is established clearly with the publication of the *Encyclopaedia* of Diderot and d'Alembert in 1751, the first encyclopaedia which reflected the modern scientific methodology. The period ends with the dominance of Portland Cement and Steel at the beginning of the twentieth century. The industry of Portland Cement and Steel brought about a revolution in the control, optimisation and distribution of building materials. This shift signifies also the decline of traditional practices in masonry construction.

In my study of the use of the technical literature in the construction of traditional masonry buildings, I divided my discussion into three key areas. These are: i) the context of the publication; ii) the content of the literature; iii) its application in conservation. In this presentation I will summarise these two first areas and I will begin to develop some ideas, not only about building conservation, but also about the relationship between traditional masonry knowledge and the history of construction.

The context

The enormous number of works concerning masonry construction published during the eighteenth and nineteenth century are the fruit of a process which started during the Renaissance with the diffusion of the printing press, and the creation of the first natural science and drawing academies. The first books on architecture emerged from the context of these teaching institutions. However, during the seventeenth century, the teaching of architecture was extended to the first «Engineer's Corps» and the military academies, the first such academy being the Danish «Holsteenske Fortifikationsetat» founded in 1684. By the end of the eighteenth century, there were military and mining schools in every european nation, as shown in Table 1.

The establishment of the discipline of military architecture led to the production of a specific genre of books. Dominated first by the Italians and the Spaniards, and later by the French and the Dutch,

TABLA 1. SCHOOLS AND ACADEMIES7

Dates	Italy	France	Portugal	Spain	Great-Britain	Germany/Austria	Americas
1700		1706 - Society Royal des Sciences de Montpellier	1701 - Academy of Fortification of Elvas and Almeida	1716 - Royal Military School of Mathematics, Barcelona		1717 - Genie-Akademie, Vienna	
	1710 - Academy of Sciences of the Institute, Bologna			1710 - Cuerpo de Ingenieros de los Exércitos, Plazas, Puertos y Fronteras (Verboom)			
	1713 - Engineering Corps, Genoa (Bassignani)	1716 - Corps des Ponts et Chaussées		1713 - Royal Spanish Academy, Madrid	1716 - Corps of Engineers (Richards)	1729 - Ingenieurskorps, Prussia (Walrawe)	
	1734 - Military Engineers Corps, Venice; 1739 - Engineers Corps, Sardinia	1740 - École des Arts, Paris *(Blondel)*				1730 - Ingenieur-Corps, Saxony	1738 - Class of the «Terço» and Class of the Artillery Regiment, Rio de Janeiro (*Alpoim*)
	1739 - Reali Scuole teoriche e pratiche d'artigleria, Piemonte	1744 - Bureau des Dessinateurs de Paris		1744 -Real Academia de las Tres Nobles Artes de San Fernando, Madrid		1731 - Ingenieur-Corps, Braunschweig	
	1742 - Military Engineers Corps (Naples)	1747 - École des Ponts et Chaussées, Paris *(Perronet)*				1747 - «Ingenieur-Corps», Austria	
	1750 - «Academy of Fine Arts, Venice; 1757 - Academy of Sciences, Turin (*Lagrange*)	1748 - École du Génie de Mézières	1762 - Classe of Nautical, Sketching and Drawing, Porto			1763 - *Accademia electoralis scientiorum Theodoro Palatina*, Heidelberg	
	1759 -Military School, Verona	1765 - Corps des Ingénieurs de la Marine	1763 - Royal Corps of Engineers (Lippe)	1763 - Royal Academy of Sciences and Arts, Barcelona	1768 - Royal Academy of Arts	1767 - School of Mining Engineering of Freiburg (Saxony)	
	1764 - Engineers Corps, Parma; 1776 - Academy of Fine Arts, Milan	1778 - École Nationale Supérieure de Mines, Paris	1765-1772 - College of the Nobles, Lisbon Courses of Drawing, Civil and Military Architecture	1777 - School of Mining Engineers, Almadén			
			1772 - Faculty of Mathematics, Univ. di Coimbra		1771 - Society of Civil Engineers, London		1779 - «Accademia de las Nobles Artes de S.Carlos de la Nueva Espagna» (Mexico)
	1786 - Courses of Mathematics, Physics & Architecture, Univ.of Pavia and Academy of Brera	1788 - École d'Arts et Métiers, Paris	1779 - Academy of the Sciences of Lisbon; 1781 - School of Life Drawing and Civil Architecture , Lisbon				1780 - American Academy of Arts and Sciences, Cambridge, EUA
	1787- Military Academy, Turin and Modena		1790 - Royal Academy of Fortification, Artillery and Drawing				1787 - Engineers Corps, Brazil
		1793 - Suppression of the Academies	1792 - Royal Engineering Corps		c. 1790 - Class of Engineering at the University of Cambridge		1792 - Royal Academy of Artillery, Fortification and Drawing, Rio de Janeiro
		1794 - École Centrale des Travaux Publics / École Polytechnique, Paris (*Sganzin*)				1799 - «Bauakademie», Berlin	

1800							
	1803 - School of Engineering, Pavia	1803 – Académie des Beaux-Arts, Paris	1803 - Royal Naval and Commerce Academy, Oporto	1802 - Escuela de Ingenieros de Caminos, Canales y Puertos, Madrid	c. 1800 - Title of Engineer at the University of Edinburgh		1802 - Military Academy of West Point
	1810-1812 - Academic Schools of Rome, «Cathedra» in Architecture		1807 - Polytechnic Academy of Oporto				1804 - University of Ohio, USA
	1811 - School of Engineering, Naples			1809 - Conservatory of the Arts, Madrid		1813 - «Königlich-Technischen Hochschule», Berlin	1810 - Military Academy of Rio de Janeiro 1816 - Royal School of Sciences, Arts and Crafts, Rio de Janeiro
	1817 - School of Engineering, Rome	1819 - École des Beaux-Arts, Paris 1829- École Centrale des Ponts et Chaussées, Paris			1818 - Institution of Civil Engineers (*Thomas Telford*) 1827 - Course of Civil Engineering at the London University College	1821 - «Gewerbeakademie», Berlin 1825 - Polytechnic School of Karlsruhe	1817 - New York Academy of Sciences 1820 -Royal Academy of Painting, Sculpture and Civil Architecture, Rio de 7Janeiro
	1838 - Technical Schools, Milan and Venice		1836 -Royal Academy of Fine Arts, Lisbon and Oporto 1837 - Polytechnic Academy of Oporto, (Passos Manuel and Sá da Bandeira)	1	1838 - School of Engineering, King's College, London 1834 - Royal Institute of British Architects, R.I.B.A.	1827 - Polytechnic School of Munich	
		1851 – Admission of engineers not public officers at «École Polytechnique»	1837 - School of the Army, Lisbon 1852 - «Industrial and Commercial Institute of Lisbon and Industrial School of Oporto Fontes Pereira de Melo	1845 - Escuela Especial de Bellas Artes, Madrid 1850 - Royal Industrial Institute, Madrid	1840 - School of Engineering, Glasgow	1840 - Polytechnic School of Stuttgart	1849 - Rensselaer Polytechnic Institute, Troy, New York
	1859 - Scuola d'Applicazione degli Ingegneri, Turin		1864-1868 – Civil Engineers Corps of the Ministry of Public Works, Commerce and Industry	1857 - Central School of Industrial Engineers, Madrid			1852 - American Society of Civil Engineers, Reston, Virginia
	1860 - Regio Istituto Tecnico Superiore, Milan; 1861-College of Builders, Milan		1869 - Portuguese Association of Civil Engineers (*João Crisóstomo d'Abreu e Sousa*)			1856 - Verein Deutscher Ingenieure, Dusseldorf	1856 - American Institute of Architects, Washington
	1865 - Special School for Civil Architects, Brera 1876 - School for Engineers, Padua		1878 - Polytechnic School of Lisbon 1885 - School of the Army, Lisbon Courses of Civil and Mining Engineering		1866 - Royal Institute of British Architects 1882 - The Polytechnic, Regent Street, London 1890 - Woolwich Polytechnic (Univ.of Greenwich)		1863 - National Academy of Sciences, Washington 1898 - American Society for Testing and Materials, US

TABLA 2. (1700-1800)

Dates	Spain	Italy	Portugal	France	Great-Britain	Germany
1700	1707-94 - Tosca, *Compendio Mathematico*	1693-1798 - Pozzo, *Perspectiva pictorum* 1711 - Galli di Bibiena, *L'architettura civile*	1712 – Bluteau, *Vocabulario Portuguez...Architectonico* 1716 – Pomey, *Indiculo universal* 1728-29 - Fortes, *O Engenheiro Português*	1691-1756 - Aviler, *Cours d'Architecture*; 1691-1826, Bullet, *L'architecture pratique*; 1694-1732 - Corneille, *Dictionnaire* 1706-14 Cordemoy, *Nouveau traité*; 1712 - La Hire, *Sur la construc. des voûtes*; 1713 - Parent, *Essais. Mathématique et Physique*;1714-Leclerc, *Traité d'architecture* 1716-65 - Gautier, *Traités des ponts* ; 1723-52 - Bion, Traité d'architecture ; 1728 - Courtonne, Architecture moderne; 1728-1858 - La Rue, Traité de coupe des pierres	1725 - Halfpeny, *The art of sound building*; 1727-56 - Langley, *The builder's jewel* 1727-70 - Salmon, *The country's builder estimator*; 1728 - Chambers, *Cyclopaedia*; 1734 -73 - Salmon, *Palladio Londiensis*;	7 1717-99 - Eiselen, *Dell'arte di cuocere i mattoni* (D)(I)
	1734 - 92 - Masustegui, Arte de Construcción; 1734 -1841- Montón, *Secretos de Artes Liberales* (E) (P)	1737 - Guarini, *Architettura Civile*; 1743-1824 - Zabaglia, *Castelli e ponti*; 1748 - Borra, *Trattato... delle resistenze*; 1748 - Poleni, *Memorie istoriche...cupola vaticano*	1739 - Oliveira, *Advertências aos modernos*	1737-1858 -Belidor, *Arch. hydraulique* (F)(D)(P)(I)(E); 1737-63 - Frezier, *La théo. et prat. coupe pierres*; 1742-43 -Le Seur,Jacquier,Boskovic, *Parere..S.Pietro*	1734 - Hawksmoor, *The builder's dictionnary*; 1734-59 - Morris, *Lectures on architecture;* 1742-1807- Langley and Langley, *Ancient Architecture*	
	1738-1805 - Briguz y Bru, *Escuela de Arquitectura*			1751-1878 - Diderot, d'Alembert, *Encyclopédie*; 1751-56 - Macquer, *Élements de chimie*; 1752-54- Lacombe, *Dictionnaire*; 1753 - Laugier, *Essai sur l'architecture* (UK) (D)	1738-50 - Langley, *The builder's assistant*; 1748-56 - Langley, *The London...bricklayers*	
	1747 - Garcia Berruguilla, *Verdadera práctica de las resol. de la Geometria*	1757 - Alberti, *Trattato della misura delle fabbriche*		1754 - Espie, *Manière.rendre édif. incombustibles* (F)(UK)(E)(I); 1755 -Belidor, d*ictionnaire*;1756 - Menand, *L'art de l'appareil*	1756-68 - Ware, *A complete body of Architecture*; 1757 - Halfpeny, *The modern builder's assistant*	
	1763-65 - Rieger, *Elementos de toda la Architectura Civil*	1760-77 - Vittone, *Istruzioni elementari*; 1765 - Sanviatale, *Elementi di architettura civile*		1761-83 - Ginet, *Toisé génèral du bâtiment*; 1761 - Fourcroy de Ramecourt, *L'art du chaufournier*; 1763 - Duhamel du Monceau, *L'art du tuilier*	1758-93 - Pain, *The builder's companion*; 1759-1862 - Chambers, *A treatise on Civil Architecture*	
	1767-1856 - Pló y Camin, *El arquitecto pratico*	1767-71 - Gallaccini, Visentini, *Trattato sopra gli errori degli architetti* (I)(UK)		1764 - Jombert, L'architecture moderne; 1766- Duhamel du Monceau, *Art du couvreur*; 1767 - Jars, *L'art du tuilier...brique*		
	1776-1805 - Bails, *Elementos de Matematicas. Dinamica e Estatica*	1772-80 - Carletti, *Istituzioni d'architettura civile*	1770 – Anon., *Sendo a cal* (P) (UK)	1770-71 - Roland de Virloys, *Dictionnaire*; 1771-77 - Blondel, *Cours*; 1771 - Gauthey, *Mémoire ...mécanique*; 1772 - Bossut, *Traité...mécanique statique*	1775 - Columbani, *A new book of ornaments*	
	1776-98 - Terreros y Dando, *Diccionario castellano con las voces de ciencias e artes*	1773 – Lamberti, Voltimetria; 1775- Griselini, *Dizionario delle arte e de'mestieri*; 1777 - Antonini, *Manuale di vari ornamenti*		1773 – Coulomb, *Essai..maximis..minimis*; 1773 - Watin, *L'art du peintre*; 1774-76 - Loriot, *Mémoire sur une découverte* (F) (UK) (D) (E) (I)		1773 -84 - Izzo, *Anfangsgrunde der burgulichen Baukunst*

7	1785 - Diez, *Arte de hacer el estuco* 1788 - Rejón de Silva, *Diccionario de las Nobles Artes* 1792 - Valzania, *Instituciones de Arquitectura*	1778-1806 - Bolognini, *Il muratore italiano*; 1780 - Preti, *Elementi di architettura*; 1781 - Lamberti, *Statica degli edifici* 1781-1853-Milizia,*Principi d'architettura civile* (I)(D); 1785 - Mascheroni, *Nuove ricerche sull'equilibrio delle volte* 1786 -Lodoli, Memmo, *Elementi d'architettura*; 1787 - Salimbeni, *Degli archi e delle volte* 1788 - Masi, *Teoria e pratica dell'architettura civile* 1789 - Ruffo, *Saggio raggionato nel origine ed esssenza dell'architettura civile* 1797 - Milizia, *Dizionario delle belle arti*	1777 - Eça, *Problema de architettura civil* 1791 - Portugal, *Sobre a utilidade da Chymica..edifícios* 1798-1825 - Viterbo, *Elucidario*	1778-80 - Faujas de S. Fond, *Recherches sur la pouzzolane*; 1783-91- Lacombe, *Encyclopédie...arts et métiers* 1786-1851-Monge,*Traité élement.de statique* (F)(UK) ; 1785 - Monroy, *Traité d'architecture civile* 1786-93 -Séguin, *Manuel d'architecture*; 1787 - Chaptal, *Observations..pouzzolanes* 1788 -1821 - Quatremère de Quincy, *Encyclopédie*; 1788-1832 - Quatremère de Quincy, *Dictionnaire historique* 1792 - 95 - Simonin, *Traité..coupe des pierres* (F)(E); 1793 - Lagardette, *L'art du plombier*; 1797 - Rondelet, *Mémoire sur le dôme du Panthéon* 1798 - Gauthey, *Dissertation.. dôme.. Panthéon*; 1798 - Girard, *Traité analyique..résistance*; 1798 - Prony,*Résultats.. expériences. Panthéon*	1780 -Higgins, *Experiments.cements.quick lime* 1781-87-Pain, *The builder's golden rule* 1791-93 - Smeaton, *A narrative of the building*	1788-99 - Von Cancrin, *Klein Technologische Werk* 1791-92 - Von Cancrin, *Einzelne Bauschriften*

these military treatises presented not only the latest and most advanced defensive and offensive systems, but also a wealth of practical information concerning the rules of masonry construction. These rules were fundamental to the fast and efficient construction of temporary and permanent military posts within war campaigns. Table 2, which refers to the works published in the eighteenth century, gives the sense of the enormous potential for cultural exchange via this literature at an international level with regard to military and civil architecture.

If this cultural exchange of information, concerning military architecture, was determined mainly by geo-political goals, in the field of civil architecture in contrast, the production of books reflects above all the diffusion of the French pedagogical model of the Académie des Beaux-Arts and the École d'Architecture. This context produced a new genre of books —text books used directly in the courses of education in these new institutions. While they were addressed to very different readers and distinctively motivated, both civil and military architecture books offered very much the same level of information regarding building techniques, together with the rudiments of geometry, perspective, measuring and estimation.

The search towards a never absolute truth which characterised the Enlightenment, brought with it the clarification of the distinctions between the different sciences: chemistry, physics, mathematics, mechanics. This rationalist impulse inspired the publication of new books dedicated not only to pure sciences but eventually also to their application in field of construction. This distinction and classification of different scientific fields and the different institutionalisation of the figures of engineer and architect, were at the origin of an increasing volume of new books. Those dedicated to geometry and stereotomy, were concerned with the theory of stone cutting. See Tosca (1707), La Rue (1728), Frézier (1737) and Simonin (1792). New texts explained the chemical aspects of limes and mortars, others presented the latest improvements in brick production. See Macquer (1751), Loriot (1774), Faujas de S.Fond (1778), Higgins (1787), Cancrin (1788) and Smeaton (1791).

The mechanical behaviour of arches and vaults along with the latest mathematical models were discussed in specialised books and illustrated with key examples. A particular issue of discussion was the stability of important domes, such as that of S. Pietro of the Vatican, and that of the Cathedral of Milan, or that of the Church of S. Geneviève (later the Pantheon) in Paris. Practical aspects of ornamentation were described in manuals specialising in coatings, renderings and paintings. Besides the creation of new classes of books, general treatises of architecture were expanded to include a larger number of chapters, which reflected the new categorisation and theorisation of the minor crafts. The craft of the fountain builder, for example, was granted an independent chapter for the first time and applied to the design of more rational sewerage systems. Moreover, new technical encyclopaedias and specialised dictionaries in Architecture and Engineering helped the establishment of common procedures and terminologies.

Following the scientific bases established in the Enlightenment, the nineteenth century gradually reflected the application and adoption of the new polytechnic engineering teaching system, organized around the practical and systematic application of the pure sciences. In the field of the construction there was a marked improvement in the mathematical models, based on collapse mechanisms, used in the graphical calculation of thrusts of arches and vaults. These models were applied not only to buildings but also to masonry bridges with ever wider spans. These publications with the latest achievements in the field of applied mathematics to arches and vaults informed also the new discipline of Resistance of (Elastic) Materials. See Girard (1798), Navier (1821), Redtenbacher (1852), Rankine (1858) and Curioni (1864). Similarly, the new discipline of Materials of Construction relied upon the application of theories of physics and chemistry to the production of traditional materials (limes, mortars, bricks and stone). Parallel to this development, the theories of hydraulic hardening were emphasised, as were the production technologies of hydraulic limes, cements and metallic profiles.

In the eighteenth and nineteenth centuries the invention of the disciplines of the history of architecture and archaeology worked gradually to demystify the understanding of the architecture of antiquity and the middle-ages. Schematic models proposed since the Renaissance in every architectural treatise, were replaced by more accurate and realistic

ones, based on actual surveys and detailed scientific evaluation. See, for example, Quatremère de Quincy (1788), Uggeri (1802), Hittorf (1835), Lassaulx (1840), Choisy (1873), Vollet-le-Duc (1875), Durm (1881), Ungewitter (1890) and Blümner (1897).

At the close of what I consider to be this golden period of the culture of traditional masonry, at the end of the nineteenth century, we have a picture of a complex and complete science for this important aspect of construction. To give a synthesis of the most important titles on general treatises, courses, stereotomy, mechanics and materials published during the nineteenth century, I have created the Tables 3 and 4. On each table, in order to indicate the period in which a publication achieved its maximum circulation and influence, the dates of the first and last edition can be found preceding the author's name. When texts were translated and published in foreign languages, these languages are indicated in brackets.

The content

Once one recognises the production context of a particular text, it is possible to better understand its content. Technical literature must be understood within its historical context which includes a recognition of the intellectual and scientific development of the period. With an awareness of historical complexity, the content of the technical literature can be read, critically analysed and translated into a contemporary terminology scientifically accepted today.

Masonry building construction can be studied following the four main steps of a complete process: 1) the design of the architectural project and the definition of the dimensions of each structural element; 2) the phase of the production and manipulation of the materials (blocks and mortars); 3) the phase of assemblage, and 4) the phase of the protection, the maintenance and the reinforcement of the building in order to guarantee its durability.

1) The definition of the project of a masonry building is concerned with the establishment of the masonry typologies planned to be used in each structural element or zone of the building. These typologies relate to the methods of block bonding (using cut stone, ashlars, coursed or uncoursed rubble, rubble filling etc.) and assembling them with mortar. In the case of vaulted structures, for example, the choice of the best designs in the plan and the sections, was made in direct relation to the preferred typology of masonry. Each one of these typologies corresponds to a limited number of ways of directing mass weight from the top of the building to its foundations. The distribution of weight was fundamental to the definition of the openings in the facade and to the positioning of vertical elements such as pillars and load bearing walls. At the same time these vertical elements were placed to correspond to both the arch and vault imposts and to the positioning of the mass foundations. These main technical aspects of the project were directly related to

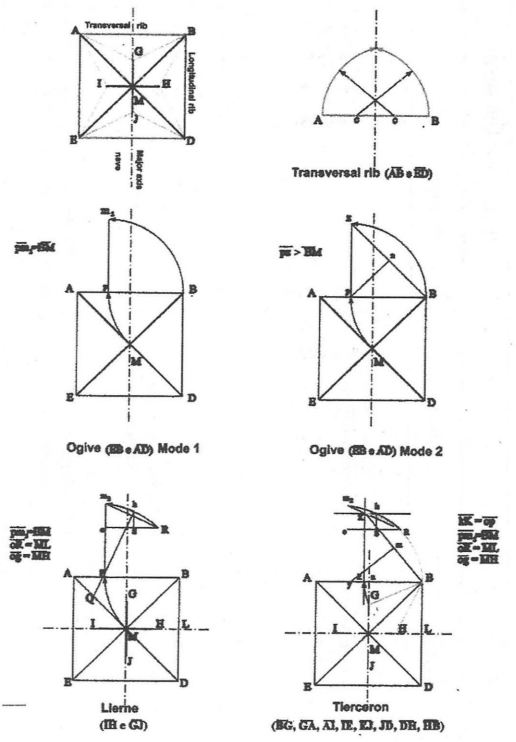


Figure 1
The graphical construction of a ribbed vault with liernes and tiercerons proposed by Frézier in 1737, reinterpreted in a contemporary and more comprehensive representation

TABLA 3 (1800-1850)

Dates	Spain	Italy	Portugal	France	Great-Britain	Germany
1800	1804 - Briguz y Bru, *Escuela de Arquitectura Civil*	1800-62 - Venturoli, *Elementi di meccanica* (I) (UK)		1800-25 - Francoeur, *Traité de mécanique élementaire*; 1802 -40 Durand, *Précis de leçons d'architecture* (F)(I); 1802-68 Rondelet, *Traité de l'art de bâtir* (F) (I)	1801 - Atwood, *A dissertation....of the Arches*; 1807-45 - Young, *A course on Mechanical Arts*; 1809-36 - Soane, *Lectures on Architecture*	1808-40 - Eytelwein, *Handbuch der Statik Festen*
				1804 - Boistard, *Expériences sur l'adhérence des mortiers*; 1804-47 - Ledoux, *L'architecture considérée sur le rapport de l'art* (F) (I); 1806-67- Sganzin, *Programme de leçons* (F) (I)	1804 - Tennant, *On different sorts of lime*	
		1806 - Stabile, *L'allievo capo mastro-costruttore*		1807 - Fleuret, *Expériences ..chaux*; 1810-15 Prony, Lagrange, *Leçons de mécanique analytique*; 1811-81 -Toussaint, *Manuel d'architecture* (F)(E)	1809 - Davy, *New analytical researches*	1809 - Poppe, *Lehrbuch der allgemeinen technologie* (D)(I)
		1813 - Antolini, *Idee elementari di architettura civile*	1812 - Margiochi, *Theoria da composição das forças*	1811-51 - Monge – *Géométrie descriptive* (F) (UK); 1811-33 - Poisson, *Traité de mécanique;* 1818 - Vicat, *Recherches exp. sur la chaux*; 1818 - Borgnis, *Traité de mécanique*	1811-39 - Quilt, *A treatise upon the equilibrium of the arches*	
				1821 - Navier, *Mémoires sur les lois de l'équilibre*; 1821 - Normand, *Le vignole des ouvriers*; 1822 - Bruyère, *Études*; 1822 - Boistard, *Recueil d'expériences*; 1822-35 - Dupin, *Applications de géométrie* (F) (D) (E)	1820 - Elmes, *Lectures on Architecture*	1819-24 - Krafft, *Anweizung zur theoretisch-praktischen zimmermanns-kunst* (D)(F)
	1827 - Villanueva, *Arte de Albañilleria*	1826 -32 - Milizia, *Opere complete*		1823 - Lamé, Clayperon, *Mémoire sur la stabilité des voûtes*; 1823-40 - Borgnis, *Traité élémentaire de construction*; 1824 - Poinsot, *Elements de statique*	1823 -50 - Nicholson, *The new practical builder*	
		1826-29- Cavalieri San Bertolo, *Istituzioni di architettura*		1825 - Hassenfratz, *L'art de calciner la pierre*; 1825-69 - Douliot, *Traité de la coupe des pierres*; 1826-35 - Douliot, *Cours élémentaire de construction*	1826 - Gwilt, *Rudiments of architecture*	
	1830 - Rio, *Memoria sobre...morteros y argamassas*	1828 -39 - Valadier, *L'architettura pratica*		1828 - Biston, *Manuel du chaufournier*; 1828 - Raucourt, *Traité...bons mortiers*; 1828 - Vicat, *Résumé...mortiers*; 1833 - Berthault-Ducreux, *Mortiers et ciments romains*	1830 - Shaw, *Civil Architecture*; 1827-39 - Nicholson, *Treatise on Masonry and stone-cutting*	
		1836 - San Martino, *Istituzioni di architettura civile*		1834-92 - Sinaud, La coupe des pierres; 1835 - Doliot, Stabilité des édifices; 1835 - Poncelet, Solution graphique..stabilité des voûtes	1833-47 - Moseley, *On a new principle in statics* (UK) (F)	1833 -Gerstner, *Handbuch der Mechanik*
	1837-59 - Piélago, *Teoria mecánica de las construcciones*			1837 - Soleirol, *Recueil d'expériences sur mortiers*; 1837 - Degaridel, *Tables de poussées des voûtes en plein cintre*; 1838 - Protot, *Cours de Architecture*	1836 - Mahan, Barlow, *An element course of civil engineering*; 1836 - Nicholson, *The principles of architecture*	

			1839-58 - Sequeira, *Noções theoricas de architectura civil*	1838-81 - Gayffier, *Manuel complet des ponts et chaussées*; 1839-86 - Moisy, Thiollet, *Vignole des propriétaires* (F)(I)(E)(P); 1839 - Blottas, *Traité complet du toisé*	1839 - Bland, *Experimental essays...in arches*; 1839-48 - Milington, *Elements of civil engineering* (UK) (F)	
	1841 - Fornes y Gurrea, *Observaciones... Arte de edificar*	1840 - Alberti, *Istruzioni pratiche per l'ingegnere civile*		1840 - Méry, *Equilibre des voûtes*; 1840 - Demont, *Traité des éléments d'architecture*; 1840 - Laurent, *Précis des cours de construction*; 1842 - Thumeloup, *Leçons d'architecture*	1840-50 - Burnell, *Rudimentary treatise on limes*; 1840-52 - Law, *The rudiments of the civil engineering* (UK) (F)	
		1842 - Giordani, *Ricordi per l'ingegnere civile*	1844 - Albuquerque, *Guia do Engenheiro* ,	1842 - Vicat, *Instruction pratique..sur.. Mortiers hydrauliques*; 1845 - Claudel, Laroque, *Formules, tables* (F)(I); 1845-79 - Dejardin, *Routine de l'établissement des voûtes*	1841 - Davy, *The architect, engineer*	
		1846-54 - Clementi, *Manuale di architettura civile*		1845-1902 - Toussaint, *Nouveau manuel de la coupe des pierres*; 1845-1926- Leroy, *Traité de Stéréotomie* (F)(I); 1846 - Vicat, *Nouvelles études sur les pouzzolanes artificielles*	1845 - Wright, *A practical treatise on mortars*	
		1847 - Reibell, *Nuovo corso di architettura*		1346 - Henry, *Principes..de dessin appliqués...maçonnerie* (F) (E); 1847 - Thiollet, *Leçons d'architecture*; 1847-98 - Mignard, *Guide des constructeurs*	1846 - Barlow, *On the existance of the line of equal horizontal thrust in arches*	
1850				1849 - Lagarde, *Nouveau manuel complet des constructeurs*	1849 - 1923 - Dobson, *Treatise on stone cutting*	1849 -1910 - Breymann *Algem. Bau-Construction-Lehre* (D) (I)

TABLA 4. (1850-1900)

Dates	Spain	Italy	Portugal	France	Great-Britain	Germany
1850	1853 - Duran y España, *Vignola de los proprietarios* 1853 - Perier y Gallego, *Tesoro de albañilleria*; 1854 - Carrillo, *Prontuario de construcciones*	1850 - Vannini, *Elementi di architettura civile*; 1850-60 - Magistretti, *Architettura civile* 1855 - De Cesare, *La scienza dell'architettura*		1850-1920 - Lagarde, *Manuel complet du constructeur* (F) (I); 1850-75 - Reynaud, *Traité d'architecture* (F) (I); 1852 - Poncelet, *Examen...équilibre des voûtes* 1853 - Carvallo, *Stabilité des voûtes*; 1856 - La Bosne, *Le guide théorique et pratique des maçons*; Roffiaen, *Traité dsur la résistance des matériaux*; 1858 - With, *Manuel du constructeur*	1852 - Shaw, *Civil Architecture*; 1852 - Hosking, Tredgold, Young, *Treatises on Architecture* 1852 - Smeaton, *The builder's pocket companion*; 1853 - Ruskin, *Lectures on architecture*; 1855 - Bullock, *The rudiments of architecture*	1852 - Redtenbacher, *Prinzipen der Mechanik*
	1857 - Amorós y Pujol, Arte de delinear y trazar; 1858 - Gotti, Curso...arquitectura....civil	1862 - Cantalupi, *Istituzioni pratiche*; 1862 - Finardi, *Prontuario*; 1864-65 - Curioni, *La resistenza dei materiali*		1859 - 1903 - Bataille, *Nouv. Manuel de la construction moderne*; 1861 - Challeton, *L'art du briquetier*; 1862 - Rivot, *Matériaux employées dans les constructions*	1855 - Fergusson, *Illustrated handbook of architecture*; 1858 - Rankine, *A manual of applied mechanics* (UK)(F); 1860-1945 - Molesworth, *Pocket-book for Civil Engineers*	1857 - Scheffler, *Theorie der Elasticitat* (D) (F)
	1858 - Scheidnager, *Noticias sobre materiales de construcción*; 1859 - Valdés, *Manual del Ingeniero*; 1859 - Espinosa, *Manual de construcciones*	1864 - Orlandini, *Manuale dell'ingegnere civile*; 1865-93 - Curioni, *L'arte di fabbricare*; 1866 - Sacchi, *Le abitazioni*; 1867 - Cantalupi, *Raccolta di tavole*		1864 - Demanet, *Guide pratique du constructeur*; 1864-1909 - Malepeyre, *Manuel du briquetier tuilier*; 1866 - Chateau, *Technologie du bâtiment*; 1867 - Durand-Claye, *Stabilité des voûtes en maçonnerie*	1861 - Fenwick, *The mechanics of construction*; 1863- Jones, *Lectures on architecture*; 1867 - Ashpitel, *Treatise on architecture*	1862-1966 - Clebsch, *Theorie der Elasticitat* (D) (F)
	1860 - Michon, *Instrucciones sobre la estabilidad*; 1861 - Rojas, *Manual de arquitectura*	1869 - Gabussi, *L'arte del costruttore*; 1870 - Gabba, Caveglia, *Corso di costruzioni civili e militari*; 1870-1912 - Musso, Copperi, *Particolari di costruzioni*	1868 - Benevides, *Tabellas..para... Engenheiros*	1868-1915 - Ramée, *L'architecte et la construction*; 1869-80 - Collignon, *Cours de mécanique*; 1870 - Dupuit, *Traité de l'équilibre des voûtes*; 1870 - Prud'homme, *Cours pratique de Construction*	1870- Bury, *Rudimentary architecture*; 1870-Mitchell, *A rudimentary manual of architecture*;1873- Burn, *Building construction*	
	1864 - Miquel y Lucuy, *Lecciones de cortes de piedras*; 1864 - Garcia Lopez, *Manual del constructor*	1871-83 - Nonnis-Marzanno, *Trattato di costruzione*	1875 - Almeida, *Materiais para construcções areia*	1871-79 - Debauve, *Manuel de l'ingénieur*; 1872-82 - Devillez, *Elements de constr. Civiles*; 1873-81 - Résal, *Traité de mécanique*; 1874-Devos, *Cours de construction*; 1874 -Moerman, *Traité de constru.*	1873-Young, *Simple methods.. calculating.. arches;*	
	1864 - Folch y Brossa, *Album de arquitectura*; 1868 - Sanchez Tirado, *Estereotomia*	1874 -84 - Cantalupi, *Portafoglio dell'ingegnere*; 1875 - Curioni, *L'elasticità nelle teorie... delle volte*	1875-77 - Almeida, *Apontamentos relativos à cal*	1874 - Levy, *La statique graphique*; Peaucellier, *Mémoire sur la stabilité des voûtes*; Bonnin, *Etude sur la stabilité des voûtes*; Bonneville, Jaurez, *La fab. des briques et des tuiles*;1877-87 - Lanck, *Traité*	1875 - Warren, *Stereotomy*; 1877- Rogers, *The architect's guide*	1875-80 - Culmann, *Die graphische statik* (D) (F)
	1868 - Ferrada, *Tratado elemental de las rocas*; 1869-97 - Ger y Lobez, *Manual de construcción civil*	1876 -85 - Ferrini, *Tecnologia del calore*; 1879 - Scala, *Compendio delle costruzioni*	1877 - Almeida, *Composição de pedras*	1877 - Gonin, *Manuel pratique*; 1877-1910 - Denfer, *Architecture & Const. Civiles*; 1878 - Belpaire, *Tables.calculs.voûtes*; 1878 - Durand-Claye, *Stabilité des voûtes*; 1880-1910 - Guedy, *Manuel marbrier*	1881 - Barry, *Lectures on Architecture*	1878-86 - Wanderley, *Handbuch der Bau-Konstruktionslehre (D) (F)*

	1872 - Rebolledo, *Construcción general* (E)(F); 1875 - Hernaez de Perea, *Manual de Perspectiva*		1878 - Alegro, *Fórmulas para avaliação.. das abóbadas de barrete de clérigo e aresta*	1881 - Opperman, *Agenda.des ingénieurs*; 1883 - Duquesnay, *Calcaires, chaux, mortiers*; 1884 - Debauve, *Procédés et mat. de construction*; 1885 - Merceron-Vicat, *Chaux hidraulyques et ciments*	1884 - Clark, *Building superintendence*	
	1877 - Garcia Lopez, *Manual de artes ceramicas*	1884 - Castigliano, *Manuale pratico per gli ingegneri*; 1884 - Melani, *Manuale d'architettura*		1885 - Oslet, Traité d'architecture;1885 - Muller, Breslau, Seyring, *El. de statique graphique*; 1885 - Genuys, *Enseignment.maçonnerie*; 1886-97 - Flamant, *Stabilité des constructions*	1885 - Kidder, *The architect*	
		1887 - Molinari, *Laterizi, gesso, pozzolane*		1886 -Hausser,Cung, *Statique graphique*; 1887 - Planat, *Pratique de la mécanique*; 1887 - Pillet, *Traité de Stéréotomie;* 1887 - Tourtay, *Etude sur le calcul des arches (F)(I);* 1887-95 - Chatelier, *Recherches sur mortiers hidrauliques*	1886 - Kerr, *The consultant architect*	
	1895 - Soroa y Fernandez, *Manual del Constructor*	1889 - Cattaneo, *L'arte muratoria*		1888- Bonnami, *Chaux hyd. et ciments*; 1888- Brune, Flamant, *Cours de construction*; 1888- Renleaux, *Le constructeur*; 1889 - Monduit, *Traité de Stéréotomie*; 1889 - Autran, *Cours de statique*; Koechlen, *Appréciations de... la statique graphique*	1888 - Addison, *Practical elements of construction*; 1888-92 - Green, *Graphics for engineers*; 1888 - Mitchell, *Building construction*	
			1892 - Neves, *Estudos sobre algumas caes hydraulicas e magnesianas nacionaes*	1890 -Oslet, *Cours de construction*; 1890 - Courtin. *Résistance des mat.*; 1890 - De Fontviolant, *Lignes d'influence*;1890-98 - Tubeuf, *Cours de construction*; 1891 - Christie, Chareyre, *Manuel de l'arch.-maçon*	1889 - Berg, *Safe building*; 1890 - Parkinson, *Structural mechanics*; 1892 - Tarn, *The mechanics of architecture*	1889 - Tetmajer, *Normen fur...Hydraulischer Bindemittel*
		1893-95 - Formenti, *La pratica del fabbricare*	1894-97 - Cordeiro, *Estudo sobre as abóbadas circulares*	1891-98 - Candlot, *Ciments et chaux hydrauliques*; 1892 - Duquesnay, *Résistance des matériaux*, 1893 - Rouché, *Coupe des pierres*; 1894 - Grange, *Chaux et sels de chaux*	1893 - Dixon, *Vademecum*; 1893 - Heat, *A manual of lime and cement*; 1893-1930 - Allen, *Practical building construction*	
		1894 - Rotta, *Manuale architettonico*; 1894 - Regis, *Taglio delle pietre*; 1896 - Levi, *Fabbricati civili*	1895-98 - Cunha, *Espessura das abóbadas*; 1896 -Leitão, *Curso elementar de construcções*	1894 - Debauve, *Procédés et mat. de construction*; 1897 - Lefevre, *La céramique du bâtiment*; 1897 - Simonet, *Maçonneries*; 1898 - 1913, Cloquet, *Traité de d'architecture*	1894 - Black, *First principles of building*	
		1895-1933 - Mazzocchi, *Calce e cementi*; 1900 - Misuraca, Albertini, *L'arte moderna del fabbricare*	1896 - Sousa, *Ideia geral sobre desmonte de rochas*; 1899 - Lepierre, *Estudo sobre a cerâmica portuguesa*	1899 - Chassagnard, *L'art de l'appareilleur*; 1900-13 - Novat, *Cours pratique de résistance des matériaux*	1897 - Harris, *The science of brickmaking*	
1900						

other better known criteria, such as distribution and function of internal spaces of the building, the project of the facade, the chosen style, the taste, the background of the designer, the economy of means.

The definition of the load bearing sections of horizontal and vertical structural elements was, until the eighteenth century, obtained using basic empirical rules. These rules were based on masonry typologies and the geometry of arches and vaults, piers, columns and load bearing walls. In general these rules tended to overestimate the necessary dimensions of the load bearing sections, in comparison to how we determine them today. During the eighteenth century, newly developed algorithms simplifying the most advanced methods, and were introduced in practical calculation of arches. These advanced methods were based on typical collapse mechanisms for circular arches which calculated the width of arch abutments (La Hire, 1712; Belidor, 1729). Other methods were developed in order to determine the size of the voussoirs (Couplet, 1729) or even the best figure of vaults (Bossut, 1770). The eighteenth century methods were improved by the introduction of a new graphical method based on the funicular polygon of forces used to determine the lines of pressure. Following the first theoretical and experimental work by authors such as Poleni (1748), Coulomb (1776), Mascheroni (1785), Venturoli (1806) and Navier (1826), this new method was developed by Lamé and Clayperon (1823), Gerstner (1831) and Moseley (1833) and further refined by Méry (1840), Scheffler (1857) and Culmann (1874) (see Benvenuto 1991, 2: 428–37). At the end of the nineteenth century, the calculation methods for masonry structures were the result of a well balanced association of empirical and theoretical methods based on approximated static and elastic principles which permitted optimisation of the resistant sections. These latest methods were mainly applied in bridges and important buildings. For the common buildings much of the calculation was still being done with the most traditional empirical methods and presented in widely circulated treatises such as the one of Rondelet (1802) or Breymann (1849).

1) The rules and processes relating to the preparation and manipulation of materials, deal with elementary stone or ceramic blocks, lime mortars and lime concrete. The work with stone blocks included, according to the particular nature of the stone, the extraction, the first quarry sorting, the cleavage observation and the respect for the natural bedding plans. This was followed by the preliminary dressing of the surfaces, the different phases used on milling to obtain the desired shape, the finishing operations, the transportation and storage. For ceramic blocks, technical literature gave all the information concerning the choice and extraction of the clay, its manipulation and puddling, the description of the different pug mill types, the advantages and limitations of each firing method in relation with the evolution of the kiln, the use of additives and the traditional quality control criteria. This literature also evaluate all the processes used in the preparation of the basic materials needed for mortars: the different types of lime, pozzolan, crushed brick, ashes, gypsum, water and sand. In particular the methods of lime burning, slaking, practical methods to obtain hydraulic mortars and the evolution of the theories of aerial and hydraulic limes hardening, were closely addressed. In addition to the description of the production of basic materials, all the procedures to mix them are detailed: the proportioning, the batching and the mixing of concrete, laying and rendering mortars, stuccos and mastics.
2) The methods to assemble blocks and mortars depended on the typology of the blocks used. Different rules were used to create the masses in foundation, the vertical elements in elevation and finally the arches and vaults. For walls and piers every bonding method was designed to optimise strength and stability in relation to the required width, guaranteeing the best imbrication of blocks and the highest adhesion between blocks and mortars. Bonding methods were also important for projecting layers or overhanging masonry elements. For arches and vaults specific bonding methods depended on the dimension of blocks, the geometry of the intradors and extradors, and the particular form of falsework structures to lay up the blocks. These methods referred to the laying of blocks

both on their edge and bed. Besides the question of bonding, the technology of vault construction considered many more important factors: centering, laying and decentering techniques, and the times required between laying and decentering. General treatises and specialised works gave enormous attention to the differentiation of the methods of raising vaults, depending on the experience of each author. D'Espie (1754), for example, detailed the construction of vaults using blocks laid on bed with the aim of creating modern fire proof buildings. Once the skeleton was executed, the masonry skin was applied. For this phase, special procedures and tools were developed to give different levels of surface finishing to stone or brick. Another class of techniques dealt with the (vertical) facing (i.e. renderings, stuccos and paint) and the (horizontal) revetment of pavements. In this later case, the maximum compaction of the foundation layers was obtained by repeated cycles of tamping, resting and watering. This procedure of compaction was considered finished when a required reduction of the original depth had been obtained.

3) Once the skeleton and the skin of the building had been completed, new techniques and detailing were used to protect and guarantee the durability of the work. Although not using a contemporary terminology, traditional builders were aware of the main deterioration processes that we know of today. In the nineteenth century there was already an awareness of atmospheric pollution due to coal combustion in the big industrial cities. In order to prevent the water infiltration intrinsic to every deterioration process, several methods were developed to protect masonry from rain water infiltration from above, the lateral incidence of the rain and from rising damp. This masonry protection was guaranteed by different techniques such as capping and roofing, drainage systems, facing against erosion and splashing, the construction of cavity walls and ventilated periphery chambers in the ground. All these protective elements required maintenance which was anticipated from the early planning stages of the project. Besides the protection and the maintenance of masonry buildings they were, when needed, also reinforced and consolidated using many of the same techniques as used in the original construction. Examples of this kind of intervention include the local reconstruction of deteriorated structural elements (eg. settled foundations, deformed piers and arches), and the introduction of additional reinforcing elements such as tie rods and counterforts.

This synthesis of the four key steps of traditional masonry building science, that I have proposed, these being, the design, the materials production, the assemblage and the protection, can constitute a

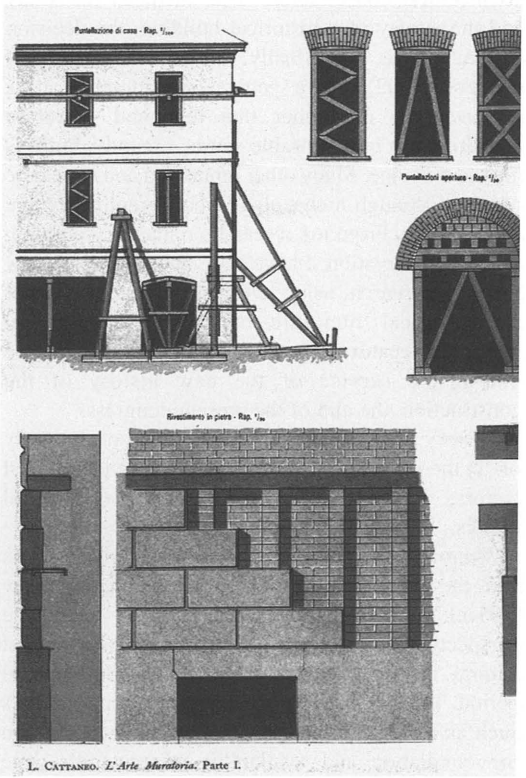


Figure 2
Example of a typical masonry reinforcement operation presented by Cattaneo in 1889. This system of provisional consolidation can be already found in the treaty of Scamozzi published in 1788 and frequently repeated by other authors as Valadier, in 1828

framework within which to categorise and analyse the content of technical literature.

Traditional masonry buildings and the history of construction

The study of the traditional construction of masonry building, that is construction before standardisation of reinforced and non reinforced masonry in the twentieth century, has been my personal pretext to read all this technical literature in its complexity of aims, and cultural and scientific contexts. My study has had a very precise and immediate practical application, this being the use of the information in the different phases of a contemporary process of architectural conservation. This includes the study and the survey of a historical building, the decision making phase, and finally, the intervention itself (Mateus, 2002). As a general consideration it is important to remember that technical literature constitutes an indispensable source of study, but it is not the only one. Many other inputs can and should be obtained through archaeology, iconography, archive research, etc. From my research on masonry building and its conservation, I have been able to outline new fields of research, using and filtering the content of the technical literature of the eighteenth and nineteenth century. These fields of research can be put at the service of the new history of the construction, the aim of the present congress.

History of construction should consist of the study of: 1) the materials; 2) the techniques; 3) ideological factors; 4) economic factors; and 5) sociological factors.

Materials: With regard to the study of materials and the concerns of masonry construction, new critical analysis can be undertaken from the perspective of the study of the characteristics of local natural resources available in a limited historical period. This analysis should also be related to factors such as trade and transportation which impact upon the circulation and availability of materials. The availability of specific materials contributed also to the local interpretation of an architectural style. This methodology, applied to masonry buildings, could be readily expanded to other types of masonry structures (bridges, aqueducts, maritime works, for example) and to other materials and structures such as structures in wood, wood and masonry, steel and masonry. Naturally, these new aims would require the expansion of the given bibliography.

Techniques: The study of techniques, via technical literature, has already been undertaken in the field of structural mechanics by authors including Timoshenko, Heyman, Benvenuto, Giuffré, and Di Pasquale. The other field of major development has been in the study of graphical representation methods by authors including Sakarovitch and Palacios. More work needs to be done in the areas of the terminology and the evolution of the tools used in different construction processes, and in the adaptation of general technology to local materials and traditions. Other fields of interest may vary from the evolution of the techniques of ornamentation and decoration, the wooden stereotomy, the traditional design of wood structures, to the different patents on steel construction during the second half of the nineteenth century.

Ideological factors: The influence of the ideological factors can be studied using technical literature as an important source. The evolution of the theorisation of styles, tastes and the political and cultural intentions of the commissioners, the designers and the builders, are well presented in the texts and illustrations of the main treatises and essays on architecture. Many of the traditional construction rules and methods were continually adapted to obtain a certain contemporary image of architecture. The question of the evolution and the interpretation of the models of antiquity and their influence on new architectural styles is by no means exhausted.

Economic factors: The evolution of construction was naturally also guided by economical factors. «Modern» methods of construction proposed by the literature of this period were presented as more economically viable in comparison with former methods and materials. This economic optimisation of processes and techniques was the key factor that determined the decline of traditional methods of construction in favour of concrete and steel.

Sociological factors: Finally, construction is the result of the integration of many different human activities. Commissioners, designers (architects and engineers) and builders were always conditioned by their own cultural background and experience in the field. Associated with these main protagonists were a huge number of professional classes of craftsmen

responsible for each phase of the complex process of construction. In the studied technical literature, much can be discovered about the stone carvers, the masons, the carpenters and the iron workers. The history of the professional and sociological condition of all these actors who contributed anonymously to this long path of experiments, failures and achievements, much also form an important chapter of the history of construction.

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Functional definitions and constructional constraints: The case of some major buildings in Portugal in the 20th century

Madalena Cunha Matos

The spatial conception of major public works has undergone a profound modification due to social, technological, and functional reasons, from the Beaux-Arts system at the beginning of the 20th century to the total success of the Modern Movement in the post war. These aspects have been well documented. While being an evident characteristic of this evolution, the role played by the materials used has been subject to less scrutiny.

The subject of this paper is the dependence on materials, as seen in the construction of two major higher education buildings in the Lisbon area: the Instituto Superior Técnico, in the city of Lisbon, designed by Porfírio Pardal Monteiro from 1926 to 1936 and the College of Education in Setúbal, designed by Álvaro Siza Vieira between 1986 and 1995. While having similar educational uses, the spatial distribution is very much influenced by the availability, transportation opportunities and skilled workers, know-how as regards to a set of chosen materials. These were stone and masonry in the construction of the IST, built in the eve of reinforced concrete's period. This last material is used, but in a subdued way and hidden from view. In the case of the Setúbal's College, it is the dominating structural material, while iron beams play in this building a similar role to RC in the Lisbon complex. A comparative analysis looks for similarities and differences in the conception process as regards the constructional constraints that a selection of materials imposes from the outset.

From local to global, an evolution is made evident with these buildings. The first one was designed in an historical period of political and economic closure, and had to depend on the 'products' of the land at a regional level. The second one was designed in the period of opening up to the outside world, following the fall of the Salazar-Caetano regime and immediately after the country's integration in the EU. The radius of availability of materials has multiplied manifold.

The dependence on material will be analysed with recourse to the architects' drawings and texts and to archival documentation.

Introduction

Detecting the constructive rationale of two major 20th century projects for educational facilities is the proposed aim of this paper. Considering a limited number of buildings may serve as an exploratory means of perusing into the nature of design processes and shedding light into the apparently disconnected historical magma of facts, expectations, and practices. The criteria of function for the selection is the result of the interpretation of this particular program —new higher educational premises— as prone to a enhanced unfolding aptitude as to the architectural creative processes of the time and also due to its variety of spatial requirements. Education for all is a desideratum glowingly aimed at by European states in the 19th and 20th centuries. Since the modern university

was contrived in Berlin in 1810, higher education buildings and campuses have become the quintessential building program of modernity. Although they were not entirely industrial-age new programs like railway stations, higher education buildings had a distinct and enlarged role to play in societal development. They also had to find a representational place in the urban fabric and establish a foundational image for the modern refunded state from the 19th century to the globalisation era. They secured national funds and, at the later stage of European reunion, international funds. They spurred a particular effort from the architects towards precise functional definition and novel representational values. From the public and especially from their sponsors, each was the object of great expectations.

Although both buildings are singular enterprises and hardly referred to by their authors as first studies in a later developed sequence, they are subject to three conditions that relate them closely to this endeavour. First, they participate in the same general tendency of the modern movement to design its buildings always as prototypes, as E. Ford signalled in his detailing's study of that period (1990). Secondly, they belong to this particular typology —the campus or the set of higher education buildings— that has been rightly exposed as a laboratory ground for modernity and even societal ideal form.[1] Finally, they represent the first opportunity for both authors to address the issue of an educational building —and think afresh about the role of architecture in the cognitive process and emotional experience of a school for late teenagers and young adults. An inaugural propensity is present. While it is manifest that the optimisation of program deals with functional and spatial definitions, its correspondence in the constructional agenda may be sought and assessed. Which materials were chosen and how were they connected? Were these materials and relationships established as a kind of statement of a preferred building system, an exploration of new technologies or simply a means of putting together space in a specific way?

Constructional concepts for 20th century architecture

The categorising of tectonic/atectonic proposed by K. Frampton for the analysis of building deeds provides a conceptual base for a study of any project. P. M. Barata carried out the report of Siza's first 20 years work using these concepts (1997). Frampton himself considered extensively the Portuguese architect's work from that perspective (1997, 1998 and 1999).

The concept of the tectonic, derived from Gottfried Semper's uncompleted architectural theory of 1860–63, naturally ignores the one material that would dominate the building industry in large parts of Europe. Steel-reinforced concrete had already been invented but had a long way to go before it became used with confidence in architecture. The singling out of four main categories of substances —textiles, ceramics, carpentry and 'stereometry' or masonry— was conceived when the constructive system which lasted for centuries was still in full vigour but was at the eve of formidable transformations and accelerations for change, in technology, building industry and architectural desiderata. It is disconcerting that a theory that exerted such profound influence should make it so difficult to study the combination of different materials, due precisely to the innovative character and composite nature of the artificial newcomer. It either assumes the role of a tectonic light frame material or its exact opposite, the heavy compressed 'stereometry'. Focussing on the articulation between materials and on the differentiation between supportive and supported elements provides a starting point through which to appreciate and compare different architectures.

L. Quaroni proposed a less complex classification as a didactic scheme (1995). He distinguished three types of building systems in relation with the structure: continuous homogeneous, discontinuous homogeneous and discontinuous dishomogeneous. According to Von Meiss in another theoretical treaty (1990), form and technique are related in five categories, ranging from glorification of technique, to technique as an image, to falsification of technique, to technique subjected and to technique tamed. I. Paricio (1997) opposes two contrasting modes of construction —isotropia *vs.* anisotropia— and surveys means of resolving the problems of internal and external corners and side façades. He focuses in the extremes of the building, the *al canto* problems —where the compositive order changes direction. When relating closure and structural elements, he proposes three types of solution's concepts— the formal, the explicit and the radical. E. Ford (1990), in

his study on the details of the modern movement and its predecessors, differentiates between the monolithic and the layered construction and further differentiates the analogous and literal treatment of the surfaces.

These different conceptualisations offer a prodigality of frameworks for an inquiry into constructional rationales of a modern period. As the subject is not prone to an indisputable determination, these concepts can best be used as a setting for the observation of the selected cases. After Perret alleged that there is no such thing as a detail in architecture, Gregotti states that architectural articulation is made visible by detail (1996). Frascari stresses the importance of the joint: in the detail resides the place of innovation: it is always a joint, always a discontinuity of material (1996).

Raw materials, structural systems and material joints are therefore the key points for an inquiry into the architectural rationales regarding construction.

The Architects

The two cases presented here are united by function and authors' prominence. The function is new buildings for a school of higher education. Both were designed by architects who are leading professionals in the Portuguese context and in their respective time: Pardal Monteiro (1897–1957) and Siza Vieira (born in 1933). Furthermore, Siza Vieira gained the international recognition that Monteiro never achieved, in spite of the fact that his work was published in influential professional periodicals such as *L'Architecture d'Aujourd'hui*.

Porfírio Pardal Monteiro was one of the first Portuguese architects to use a modernistic language, and one of the few who consistently did so throughout his career. However, his was a not a homogeneously inspired production. When compared with contemporaneous architects, he is known for the rationalistic expression he gave his numerous projects, most of which were *de facto* built: maritime stations, churches and seminaries, middle class housing blocks, hotels, and. above all, public institutions and government buildings. He enjoyed the reputation of having a fairly well organised architectural office, and employed a few of the soon to be independent architects in the Lisbon scene. His text on the architects of the reconstruction of Lisbon following the 1755's earthquake acknowledge his inclination towards regular, repetitive procedures and an *esprit de système*.[2] Although his first designs exhibit a richness of materials and detail —such as the CGD's banking institution in Oporto or the Av. 5 de Outubro's villa in Lisbon, he later evolved to a dry, stringent monumental architecture.

Álvaro Siza Vieira is known in the international scene since the 60's, initially mainly from Portuguese, Spanish and Italian architectural publications. He has claimed another level of freedom —which translates into an iconographic catalogue that borrows further and further into the whole world and also into a prodigiously expanded temporal scale. Figure 1.

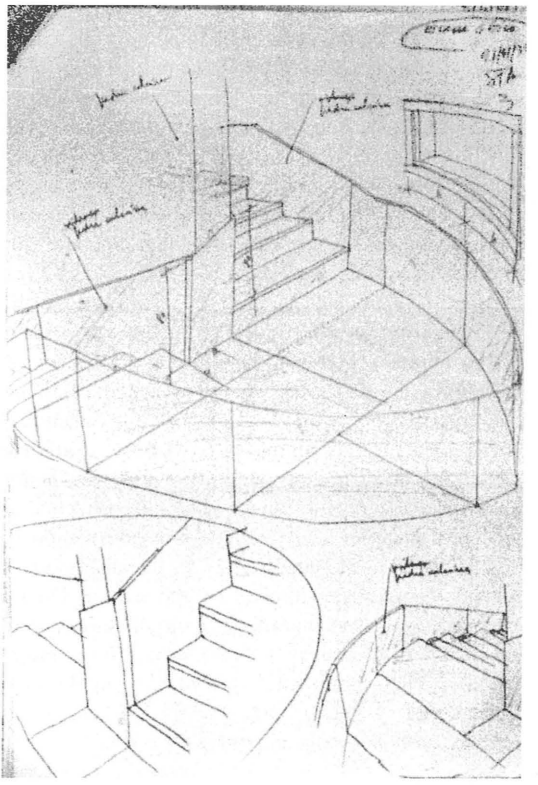


Figure 1
The 'Gothic' staircase: tradition reinvented (ESE). Working drawing by Siza Vieira

Functional Definitions

Monteiro's 'Instituto Superior Técnico' (IST) became the new site for the existing school of engineering of the capital city and its planning and building process lasted from 1926 to 1941. Classes started in the newly completed pavilions in 1936. Siza's Teacher's Training College in Setúbal (ESE) was designed and built between 1986 and 1995.[3]

In both cases, a collection of similar rooms, with *quasi* equivalent requirements[4] in light incidence, air renovation, sound insulation, gross area, volume, etc., combines with a collection of *atypical* rooms programmed for very definite functions —the large lecture hall, the laboratories, the workshops, the administrative and the management sectors, the sports hall, the housing units for keepers or guests. Circulation and social areas allowing for the functioning of the premises constitute a more flexible requisite.

The plots being quite generous in both cases excluded the need to occupy them intensely. The spreading out of the various parts of the buildings is analogous. It is therefore possible to look into the functional *vs.* the constructional constraints without the interference of limitations in substructure area.

The making-up of the design brief was very diverse in the two cases. In the ESE, the long experience in higher education facilities by the Ministry of Education provided a relatively straightforward mechanism for defining the quantitative and organisational contents of the program. In the case of IST, however, the absence of recent precedents in the country led the architect to perceive the functional requirements' study almost as a work by itself. He went for a long journey abroad, visiting the major engineering schools in Europe. The only evidence of an internal survey and dialogue is a notification to attend signed in 26 August 1927 by the all-important recently empowered director of the school, Duarte Pacheco: professors and other faculty members were asked to draft reports for the project's program. Another letter addressed to the Ministry of Foreign Affairs asked for assistance from our embassies abroad to obtain plans and other data from 'modern' engineering schools. The whole process of programming and building was removed from the everyday knowledge of even the school's faculty, as can be deduced by the reading of the record of proceedings. Nevertheless, an innovative brief was proposed, of large laboratories and lecture halls, of an indoor swimming pool and sports ground, of spacious classrooms and workshops and generous circulation areas. Carefully designing the equipment went so far as to incorporate the entire furniture in the design and production, which took place in the actual school workshops.

Taken in a comprehensive meaning, functional definition also entails the sign value. The symbolic purpose in Lisbon's IST was twofold. In filigree, to express and reveal the engineers' rise to power in a society dominated by Law School alumni. And to give impetus to a planned urban expansion to the Northeast of town, assuring an important part of the role of Lisbon as capital city on a colonial scale. Figure 2.



Figure 2
Opening up a rural area for urbanisation. Final stages of work (IST). Photograph from Porfírio Pardal Monteiro's Archive

In the ESE, democracy is at work. Political turmoil was still very intense in the aftermath of the 25th April 1974. The industrial crisis of the Setúbal peninsula provided a developmental role for the new school. Highly determined patrons in the school administration were able to secure the commission from their chosen architect and to obtain the funds which were necessary to respect the project's level of finishes.

Constructional Constraints

The availability of materials, their mode of transportation, the level of craftsmanship, the type of contract are all factors impinging on the selection of a set of materials and building system.

Materials and building system

The building system in the IST is a compromise between load-bearing walls and concrete floors. Stone, brick and rubble masonry are used in the walls and reinforced concrete is used in beams, in a number of pillars and in floors. These are made in solid concrete slabs, either simple or combined with beams. The masonry is covered with stucco on exterior and plaster in interior. Figure 3.

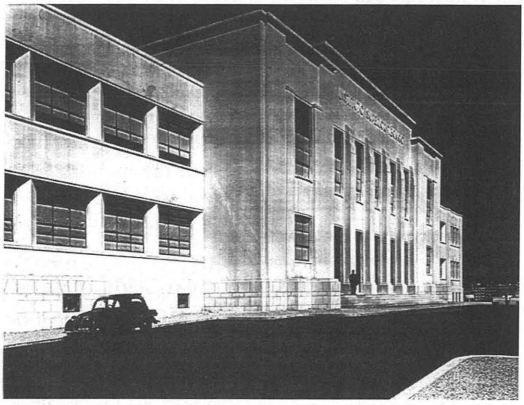


Figure 3
The Central Pavilion upon completion: bearing walls go modern (IST). Photograph from Porfírio Pardal Monteiro's Archive

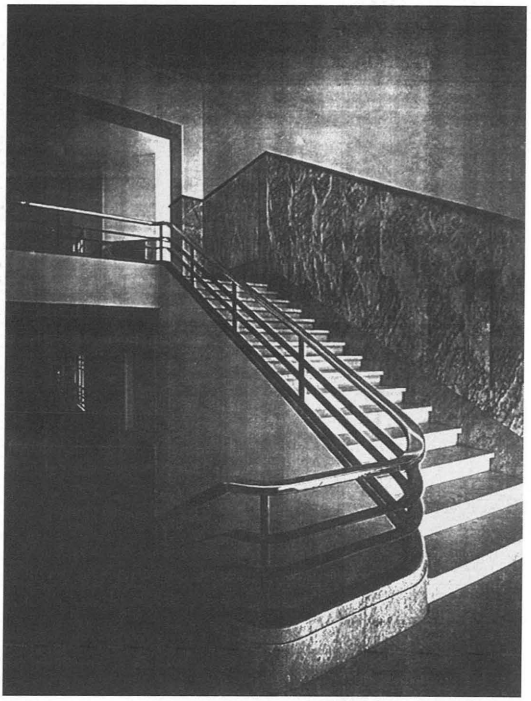


Figure 4
The interior staircases and the excellent craftsmanship of their revetment (IST). Photograph from Porfírio Pardal Monteiro's Archive

Another important material is stone. It is employed in the limestone base of the buildings, in which case it is disposed in alternating layers and wedge-shaped voussoirs over the windows; as marble floor mosaics in circulation areas; as marble and Algarve's and Estremadura's *brecha* veneers in the revetment of the grand hall, Grand *Salon* and stairs; Figure 3; and in smaller applications such as window sills. Ceramic is used in the coloured tiles lining the floors of the basement floors. Iron is used in the door and window-frames and their gratings, in the structure of the suspended glass ceiling covering the great hall, in the gates and railings surmounting the exterior walls; and in the open-air lamp-posts. Steel is used in the railings protecting staircases and galleries, and in the door handles and other fixtures. Cork is used in the floors of some major spaces, designed as a mosaic. Wood is used in classroom floors; in the handrails and banisters of staircases of non-central pavilions; and in the smaller windows-frames in the lower floors. Plaster is also used in the uniformly painted decorations in the façades.

The ESE is built using reinforced concrete extensively in walls, columns, floors and roof slabs. Figure 5. It takes the place masonry had in the IST. Stone is used in veneers around columns in wainscots and in floor surfaces. Iron is used in door and window-frames and various railings. Wood is used in panelling areas and in interior doors and fittings. Figure 6. Cork is used for the floor in most of the rooms.

Type of contract

The IST's director, the electrotechnic engineer Duarte Pacheco, personally managed the works.

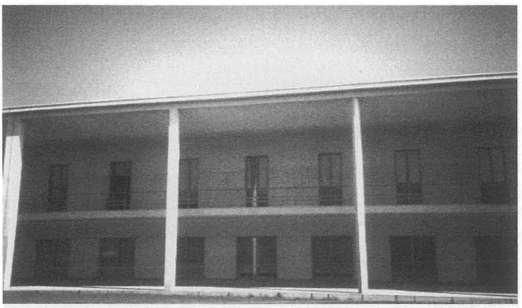


Figure 5
Steel-reinforced concrete as an almost total material (ESE). Photograph by Madalena Cunha Matos

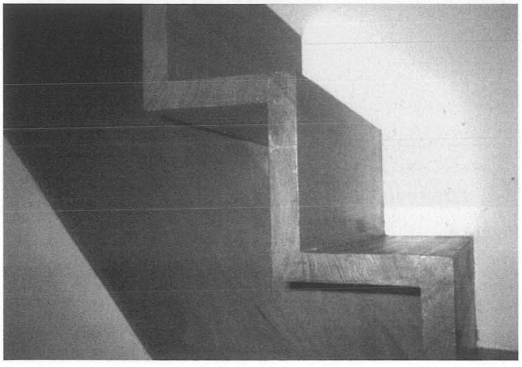


Figure 6
A number of 'mechanisms' such as the guest's and the library's steep staircases are made entirely in wood (ESE). Photograph by Madalena Cunha Matos

In 27 November 1929, the first stone for the central pavilion was laid down.[5] The earth movements and excavation had begun in July 1927. The architect was commissioned the project in November 1928. The work was finally completed in all its exterior arrangements in 1941, two years before Pacheco's untimely death. A remarkable amount of more than a hundred suppliers were registered.

In the ESE, the traditional procedure of contracting a building company was adopted. Young civil engineers were in charge of the work in the building site.

Transportation of materials

The ease of transport depends on the relative location in the city. The IST was built in an urban fringe, soon to be a booming middle-class residential quarter. It had various public transports, but the site itself was farmland. The beginning of the work coincided with a dramatic financial crisis of the Portuguese State that would eventually lead to the dictatorship of Salazar. We can infer the difficulty of procuring the necessary vehicles for the earth movements from the correspondence sent from the school in 1927. In a letter, director Pacheco asks the Minister of Commerce and Communications to lend the school a digging machine belonging to CP, the railway-lines company. In fact, an important railway-line ran near the future school and soon plans were made to implant one of the main railway stations just outside the school grounds, with a purpose-built branch-line. Pacheco also wrote the Leixões's port authority asking for 20 to 30 wagons for the levelling of the ground, also as a lease; he insisted three times until supposedly he got what he wanted. The difficulty and expense of earth disposal led to replacing the maximum volume in site and promoted the solution of the site surface treatment in platforms, grandiosely leading to the central pavilion, the compositional climax. Figure 7. Earth, the first building material, set thus the tone: economy was the aim. Portuguese materials were given preference.

The ESE was located outside Setúbal in an almost totally rural setting at the time; but it had roads that could be negotiated by heavy-goods vehicles.

Availability of materials

Using RC in parts of the IST buildings leads to the conclusion that sufficient know-how and workers' skill was available to use this building system. It was the shortage of iron in the market and economic reasons that led to the masonry alternative. Monteiro endorses the decision by declaring in 1934 that masonry construction really costs very little. A well-known story tells how Pacheco built his school using the samples he asked from various furnishers. However implausible this story, he certainly summoned officially all the firms of ceramics listed in

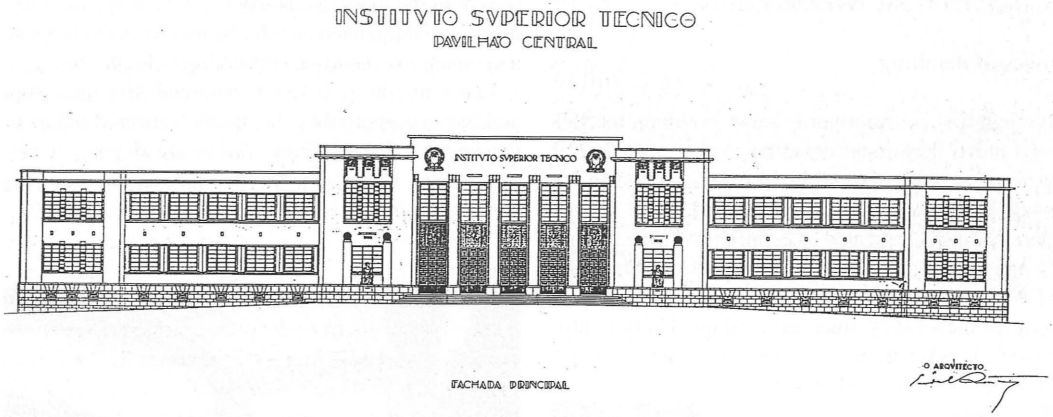


Figure 7
The imposing façade of the Central Pavilion (IST). Original elevation by Porfírio Pardal Monteiro

the Lisbon's Commercial Directory in September 1927, well before actual building began; later perhaps he ceased to render account of his doings to his colleagues. The scarcity of resources was also likely eased, due to the loans extended to the IST by the banking institution Caixa Geral dos Depósitos and to the financial operations that made possible the urbanisation and plot selling of the rest of the original farms by the school.

In the ESE, the disappearance of political and economic frontiers inaugurated a European-sized market. New materials were arriving every day to the country. It was one of the first pedagogic buildings to be thermally isolated in a PVC composite in all the exterior surfaces. The novelty of this new market was still not completely assimilated. Ten years of instability and economic difficulties had set a pattern for the building industry. Efforts were mainly made in controlling quality in the finishes throughout the school, not into the experimentation of new materials. The set of materials was limited and familiar to the architect.

Skilled workers

In the IST, providing jobs to the maximum number of workers was the welfare policy put into action, well before the New York's crash and subsequent Depression. A battalion of unemployed workers was given a low-paid job. At its peak, there were 700 workers on site simultaneously.

Yet, some excellent craftsmanship can be found in the buildings: mainly the stereotomy of the ashlars, the metallic fittings and the ceramic floors. The architect had a particular relationship to stonework. The extraction, carving and setting of limestone and marble had been a family business since 1888. It was located in Pero Pinheiro, Sintra —approximately 40 km from the capital— where Monteiro lived as a child.

In the ESE, the period of building corresponded to a reversal of the emigration direction, from outward to inward bound. The mass emigration of the skilled workers, at its peak by the middle and end of the 60's, had ceased. From 1975 onwards, the country integrated a significant population of ex-colonials and of African-born Portuguese descendants (the 'retornados'). A steady flow of African emigrants from the ex-colonies began. A building site's view was likewise altered: an incongruent mix between old skilled workers and small subcontracted firms with newly arrived emigrants who didn't speak the language. The strict modulation of the project and the complete gridiron drawn stamped across all the architectural drawings might be related to the potentially confusing situation that building sites were beginning to exhibit and to the proliferation of subcontracting. The project is subject to a strict three-dimensional geometry.

An architectural interpretation

Modes of detailing

Although it is an avant-garde set of building, the IST keeps much traditional detailing in the profusion of cornices, pilasters, mouldings and reveals; and in the design de *per se* of the main non-pedagogic rooms, where ceilings are treated as a unifier of space. Figure 8. Heavy plastered geometries are suspended in wood structures, in a clear continuity to the 18th and 19th centuries elaborately stuccoed ceilings. Unity is also sought in the modern classrooms, where apparent RC beams are duplicated as false beams so as to compose a symmetrical pattern in the ceilings. Figure 9.

Every marble wainscot is trimmed. But the heavy architrave supported by the marble veneered pillars in the grand hall and Grand *Salon* are devoid of any transitional tropes: the capital is suggested by the slight glide upwards of the front veneer. Figure 10.

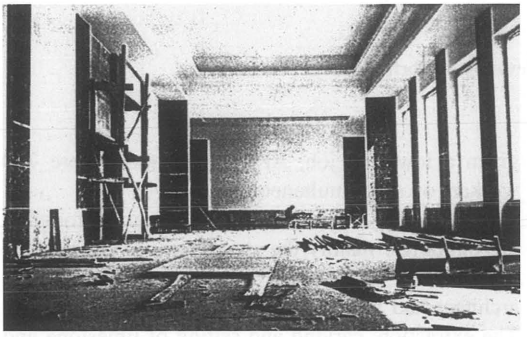


Figure 8
The Grand *Salon* under construction: the ceiling as an unifier of space (IST). Photograph from Porfírio Pardal Monteiro's Archive

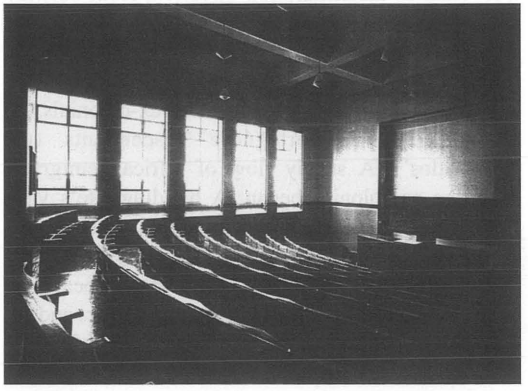


Figure 9
An amphitheatre. Structural evidence of RC in symmetrical beams' patterns (IST). Photograph from Porfírio Pardal Monteiro's Archive.

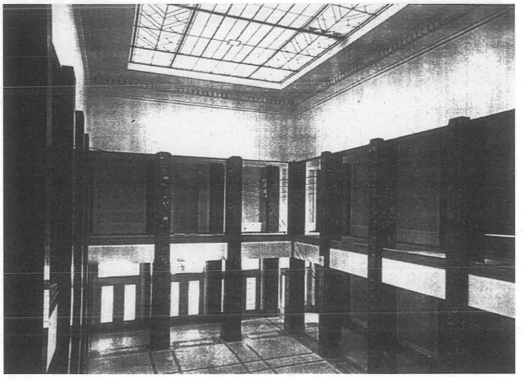


Figure 10
Suggestion of capitals in the Grand Hall (IST). Photograph from Porfírio Pardal Monteiro's Archive

Modern detailing is overtly used in the entire metallic door and window-frames and in the treatment of the exterior surfaces. Arts Deco is a conspicuous influence in formal motives, colour selection and combination of materials; above all, in the delectation of veneered stone in diverse types of patterns, colour and marbles combinations. Mies van der Rohe's 1929 Pavilion had fostered the precious materials appeal. The 30's would see a proliferation of marble veneers facing the housing building facades in Lisbon, mainly through the production of architect Cassiano Branco. In some cases, heavily veined marbles in black and white patterns or other strong colours were used. It was a time for the discovery of the abstract play of veins in stone. In the IST, veneered wainscot in circulation areas and enclaves created by the main staircases and water distribution fountains are also reminiscent of Loos.

Very few working drawings have survived, although a family-owned architectural agency has

maintained the archive in order. In the remaining plans and sections, neither infrastructure networks or structural elements are indicated. Figure 11. The absence of detailing drawings is not so surprising for, as Edward Ford states, when craftsmanship died, detailing was born. And this was still a highly 'crafted' architecture, notwithstanding its modernistic simplification and abstract character. Beside a reduction of the door and window-frames, only hewn stone is drafted one by one in the elevation drawings. Figure 12.

In ESE, a limited number of materials, encompassing the preferences for the white stuccoed volumes, sustain a logic of lightness and evanescent materiality. Few clues are given as to the passage of AC ducts or other networks. Suspended plastered ceilings creating their own designs hide away the technical ducts. No beams are apparent. Columns always support strictly flat planes, even if they are tilted or covering an exterior area. Steel I beams are used in some large spaces, but they are covered up too by the 'neutralising skin' of white plaster. Even the exterior thermal insulation helps to maintain the neo-modernistic formal aspect.

Even if stone is no longer used as a bearing material but as a veneer, a hint of pleasure is perceptible in the choice of its setting, in the detailing of its geometry, in the rhythm of its quasi-imperceptible joints. Figure 13. Frampton alludes to the very corporeal metaphor of a 'breath' (1997). These details invite to follow and decipher them, eventually to find their hidden logic, eventually to be caught in a game, an amused sort of contemplation. Loos is rightly cited in the revetment game of the later works of Siza, but the use of that revetment as a means of creating a translucent space is also related to Terragni's Casa del Fascio.

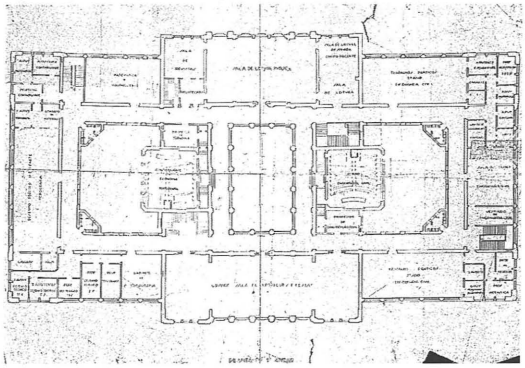


Figure 11
Plan of Second Floor. Central Pavilion (IST). Original drawing by Porfírio Pardal Monteiro

Expressions

The IST is a grand essay in Monteiro's career: his subsequent projects would transport the institutional gravity, even heaviness that is so evident in the way he found of settling these buildings on the ground.

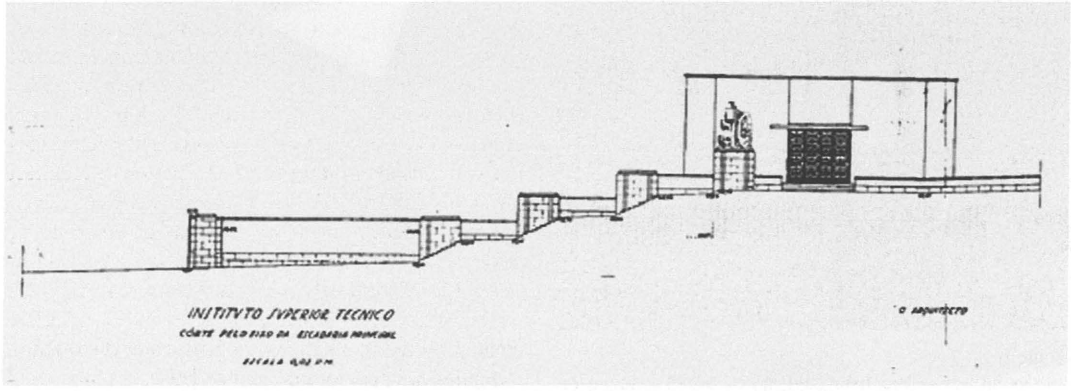


Figure 12
Main entrance to the building complex. Side elevation of staircases (IST). Original drawing by Porfírio Pardal Monteiro

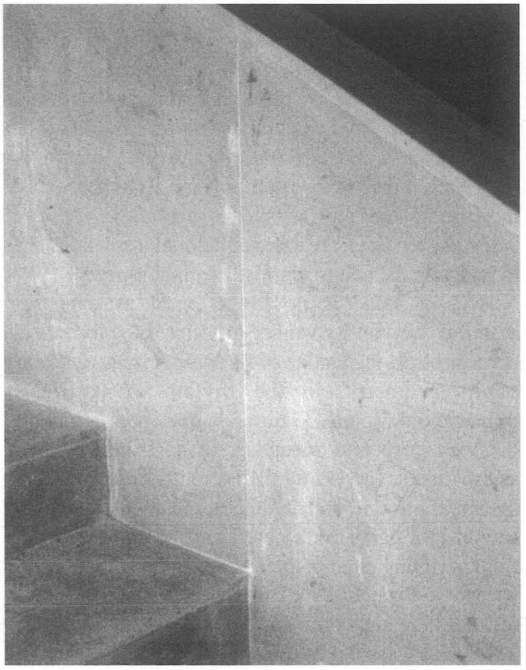


Figure 13
The quasi-imperceptible joints in the veneering of an interior staircase. Final stage of work (ESE). Photograph by Madalena Cunha Matos

The work occurred when a tide of law and order values was overwhelming the country. The earthen, telluric bearing wall stands firmly against instability and menace.

The ESE, contrarily, gives a sense of openness, transparency and accessibility. The revealing of structure in the shape of slender columns joyfully designed in different ways and pointing in different directions only reinforce the optimism, the promise of happiness that the it carries. In a sense, the whole light organism is an aerial frame. It is true that it is made up of pure, abstract volumes. But in the roofs these volumes turn imperceptibly into planes and perform a plastic display: they get curved, they zigzag. Figure 14. And so do they get slanted and twisted and fragmented near the ground. In some places, volumes disappear and turn completely into planes, which gain movement and drag nearby elements into their motion.

Concluding remarks

These projects show the artistic personalities of their creators but also reflect the material conditions, the self-confidence and the expectations of a country in very different phases of its history.

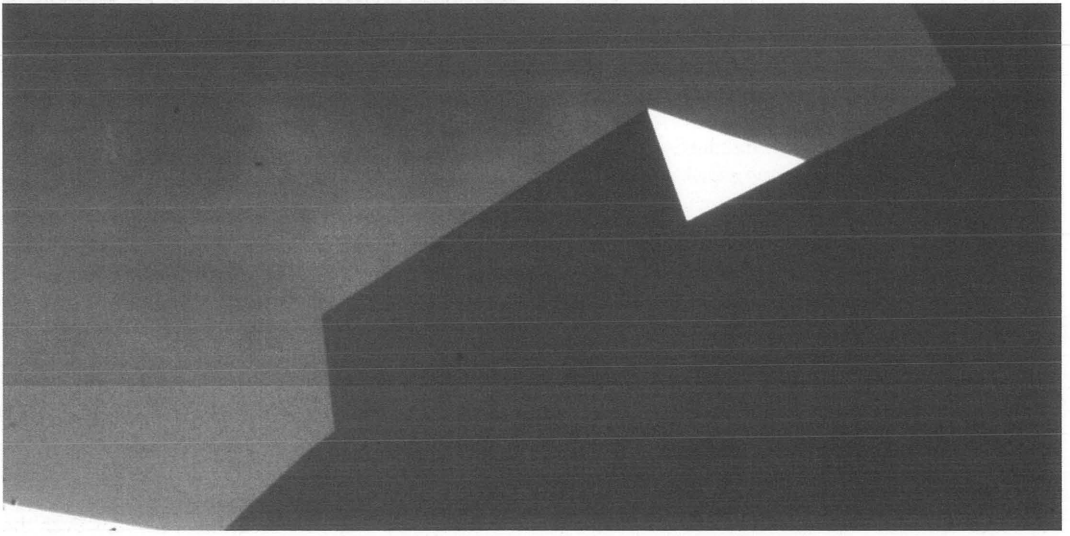


Figure 14
Broken skyline resulting from the gymnasium's roof structure in steel I beams (ESE). Photograph by Luis Patrício Costa

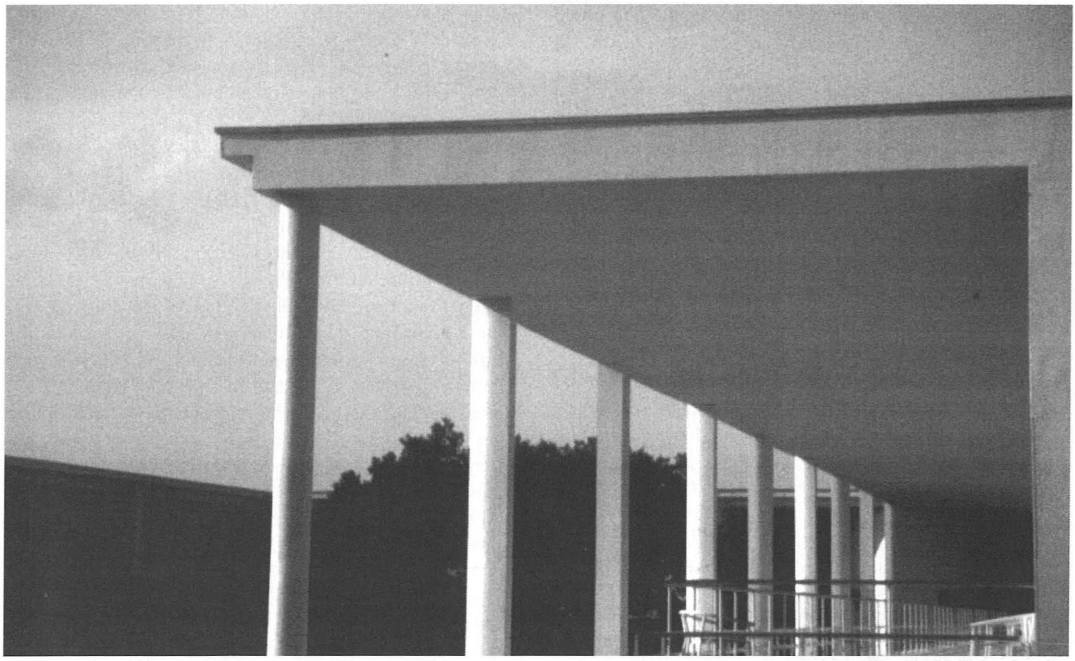


Figure 15
Columns against flat planes (ESE). Photograph by Madalena Cunha Matos

The first project is situated in the last period where the system of sustaining walls could still be seen as a trivial answer to a problem of construction. The ESE project is worked out in a period where RC porticated construction is overly dominant in the country and has acquired the status of 'traditional' constructive system. The break that this building proposes is understated, for it neither aggressively exposes alternative modes of building —which in fact it uses— nor does it even suggest that the issue of building technology has in any way a leading role in the process of its design. Quite the opposite: in strictly technical terms, the ESE building seems to push the RC almost to its limits —in the use of its plastic capacity, projecting negatives and positives, holes and tropes, thin sheets of a material that curves and bends and folds and retreats its beams into itself. Like Mies in his European phase, it is rather the sculptural relationship of the column to the horizontal or vertical bare plane that seems to be the point and not the systematics of any building process. Figure 15. The fact that RC is used throughout the building, in walls, floors, columns and roofs and not in a porticated pattern is concealed by the evidence of columns, pillars, elements of repetition and rhythm.

Space shaping and form giving appear as the desiderata in this instance. The constructional means assume a subdued position in the creative process. Reference to precedents and to the exposition of alternatives dealing with the relationship between structure and closure —namely, the '4 ways' drawn by Le Corbusier— can be found in the project.

The case of the IST is a paradox —being largely constructed through a time-honoured technique and with the same materials used centuries ago *and* offering an image of absolute modernity. It is moreover a vivid demonstration of the capacity of architecture to transcend the limitations of a given time.

In both these major works of educational and research facilities, the exploration of a formal and spatial agenda is at the foreground; perhaps even the symbolic role they are expected to perform is more important in the process of their design than

constructional consistency. The constraints of place and time weighted heavily in the selection of materials and building process. But what was sought was more important than how it was done; and perceptible unity and consistency there was, as well as *firmitas*. Architecture does not dispense with logic, but makes do with fragmentary logics.

Notes

1. Ref. for example the inaugural issue of *Astragalo* (1994).
2. Ref. the Urbanism and Housing Congress held in 1944 in Madrid, Lisbon and Seville, P. P. Monteiro (1945).
3. For an analysis of these two buildings, of their architectural materials and strategies, ref. M. C. Matos (1994) for the IST design and ref. M. C. Matos (1995) for the ESE design.
4. Considering the ideal standarts of their own time.
5. Ref. *Quinze Anos de Obras Públicas,* p. 39 (MOP, 1948).

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A matter to be considered in various directions: Approaches in design, prefabrication and assembly of the Hamelin Chain Bridge, 1836–38

Michael Mende

Demands of an Increasing Traffic

In December 1817, only three years after Hanover had been restituted as kingdom within the German Confederation created as a result of the Vienna Congress, Victor Leberecht Prott (1781–1857) as an engineer lieutenant colonel the technical chief of the General Board of Roads presented his general road construction plan (Hindelang an Walther 1989, 14). His proposal was to improve the communication in that kingdom by laying out a net finally comprising about 3000 km of main roads and more than 2000 km of secondary or connecting roads. At this moment only 920 km of these roads being composed of a bottoming between kerbstones and paved with sand, gravel, or limestone were opened to traffic.

In the former electorate of Hanover road construction had started during the 1760s just after the Seven Years' War. Between 1764 and the early 1780s three main lines were going to be completed under supervision of the Royal Electoral General Intendance of Road Construction established by a grant of George III. The reason for taking up the roadworks was of both military and commercial concern (Baldermann 1968, 75). Whereas the roads running from the capital to the fortified cities of Hamelin and Nienburg watching the river Weser were more of military importance, the road passing on its run south to Cassel the Hanoverian towns of Einbeck, Northeim, Gottingen, and Munden, would be more of commercial interest. About 1830 goods transport on the road from Hanover via Northeim and Gottingen to Cassel or destinations in Thuringia made approximately 6,000 tons a year, while a little more than 2,000 tons annually were crossing the Weser at Hamelin to get their destinations in Lippe or eastern Westphalia (von Reden 1839, 2: 301 and 321). In the long term Hanoverian efforts in road construction would shift the main link between the seaports of Hamburg or Bremen and trading centers like Frankfurt on the Main or Nuremberg from its traditional route via Brunswick more to the west focusing the capital and the Leine valley (Scholl 1978, 46). Following a policy of pushing long distance transit routes Hanover tried to keep the goods transport as long as possible within the borders of her territory. Hoping for raising benefits from a transit trade dragged out in such a way, the kingdom was going to convert roads into a new kind of staples (Rauers 1913, 29 and 42).

Before the Hanoverian exchequer, however, would be able to meet those expectations, heavy investments were to be made not at least into bridge building. As each of the three 18th century roads merely had to cross brooks or creeks, for the time only small stone arch bridges would have become necessary. For passing rivers like the Rhume at Northeim, the Werra at Munden, or the Weser at Nienburg and Hamelin furthermore existent bridges could be used, but which in 1817 each still had remained in the property of those municipalities. Albeit they were raising tolls, the bridges, however, lacked constant maintenance

and therefore appeared in more or less a rather bad condition. Largely of medieval origin almost every of these stone arch bridges by that time even had undergone considerable decay. Damages caused by heavy ice motion, flood, or military action during the Napoleonic wars had added to. In particular most bridges had lost at least one of their vaults and sometimes also one or, like that at Hamelin, even two of the piers. Because the municipal budgets could not afford more, strut frames had to compensate for. Albeit better than a ferry such structures, as chosen for the bridges at Northeim, Nienburg, and Hamelin, as well as at Minden, the Prussian fortress watching the river Weser downstreams Porta Westfalica, were nothing more than rather a stopgap solution. If one of them fully would have to be replaced by a new structure, first the state had to take command. In the case of Hanover this meant that the General Board of Roads then would become responsible for the entire project, the design as well as construction and further maintenance or frequent repair.

Soon after the French occupation troops had withdrawn from Northwest Germany the bridge at Hamelin anew would have to undergo at least sweeping repair, a measure which had become unevitable as Hanover by the agreements of the Vienna Congress was obliged to take care of the improvements necessary to enable both an unrestrained navigation on the river Weser and an open communication for troop movements between Prussia's central and western provinces. Whereas the character of the Weser as an «international» river formally would get confirmed by the Weser Navigation Act of 1823, the communication crossing that river at Hamelin would become one of the eighteen most important routes mentioned by Prott in his 1817 proposal.

At this moment seven of the German states of quite a different size and political impact were neighbouring the river Weser: besides Hanover also Hesse-Cassel, Prussia, Brunswick, Lippe and Schaumburg-Lippe, finally Bremen and Oldenburg. Then bridges were crossing the river only at six points, most of them located in Hanover. Apart from Hamelin and Nienburg there existed also bridges downstreams at Hoya and upstreams at Munden over the river Werra, just before it is joining the river Fulda and both shape the Weser. Each a single bridge was crossing the river at Bremen, at Rinteln in the Hessian exclave of Schaumburg, and at Minden in Prussian Westphalia, while the bridge at Hoxter upstreams in the same province since 1673 had kept ruined (Grunsky 1998, 108).

Adopting a New Type of Bridge Construction

According to the agreements made among these states by the Weser Navigation Act none of these bridges should present an obstacle to shipping traffic. Albeit first attempts to sail by steam boat had been made in 1816, both passenger traffic and goods transport on barges towed by a paddle wheel tug sustainedly would become successful only since the late 1830s. Within a few years, however, Hamelin then would become the dominating location for steam navigation upstream of Bremen. Compared with the barges of the trains until the mid 19th century generally used for goods transport, the paddle wheel passenger boats and tugs would be much broader. Considering the design of a new bridge that meant above all to diminish the number of its piers and so to widen its openings, both by the way also a precaution against damages by heavy flooding or ice motion. At Hamelin this aspect was of particular importance because both the holm deviding the river Weser into two arms and the falls at their entrance. Controlled by weirs across both arms these falls were powering mills located as well on the holm as at the townside wharf, whereas locks installed 1732–33 allowed that boats could pass without lightening.

The Hamelin bridge therefore not only was to take over one of Germany's soon main through roads running from east to west, but also to give furthermore free access to the holm with its mills and locks. Designing a new structure of this bridge had to consider that the number of waggons, carts, or carriages passing it presumabely would increase and beyond that their load could increase, too. Whereas in 1822 the performance of a horse was estimated at 0.5 to 0.8 tons, in 1830 it would have been 1.2 or even 1.4 tons, so that a waggon pulled by four horses on a stone paved road, of which Hanover at this moment possessed totally a little less than 450 km, might have been loaded with up to six tons of goods (von Reden 1838, 2: 345 and 380).

At the beginning of the 19th century the Hamelin bridge was a timbered super structure on stone piers.

Its western part comprised five trusses and four river piers, the eastern part connecting the city with the mill and lock holm besides each two trusses and piers also a double flap bridge with the lifting gate on a timbered pier in between both its decks. As in the course of the Napoleonic Wars each part of the bridge had lost one of its piers and two of its trusses, both the municipality and the General Board of Hydraulic Engineering soon after the armistice was urged to consider repair and beyond that improvements, too. In a way following out the proposals made in January 1818 by Lock Commissioner Anton Heinrich Dammert (ca. 1755–1828), the remains of the destroyed piers as well as the flap bridge were abandoned and longer, but still timbered trusses took the place so that on each side a passage of about 33m could have been received (Hausmann and Plath 1973, 50; NHStA Hann 109, 1028 and 13b/Hameln 6pg).

Apparently the renewed structure merely a couple of years later again would need radical repair. By their report of April 1824 Anton Heinrich and Richard Dammert, both sons of the Lock Commissioner and as engineering officers working with Prott and the General Board of Roads, therefore argued for a cast iron bridge (NHStA 109, 1028 and 13b/Hameln 8pg.). Their project was inspired by Thomas Wilson's bridge of 1796 over the river Wear at Sunderland. This cast iron bridge basing on Thomas Paine's design and consisting of six ribs, each made up of 105 iron blocks casted again at the foundry of the Walker brothers at Rotherham (DeLony 2000, 43), was by its single-span of 72m at that time not at least for German eyes a still spectacular feature.

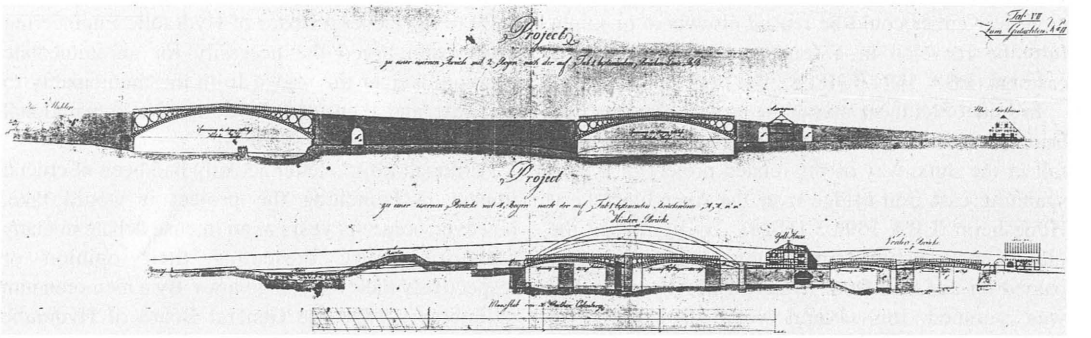


Figure 1
August Heinrich Dammert and Richard A. Dammert, two alternatives of the proposed cast iron bridge, plake VII of the report No 2, 1829 (NHStA 13b/Hameln 8pg)

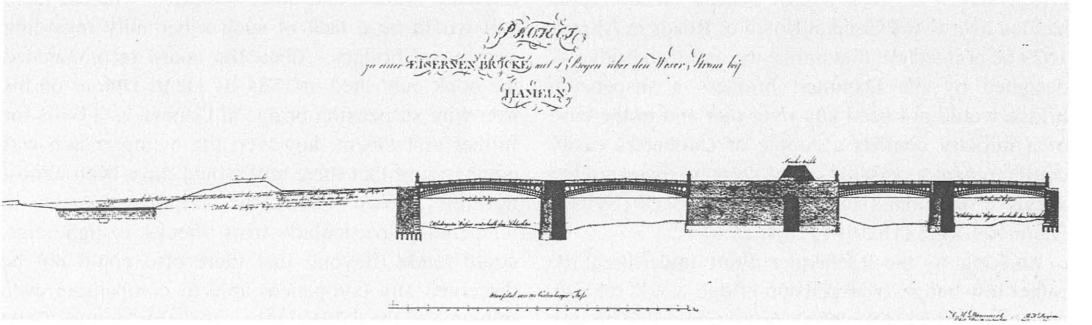


Figure 1b
August Heinrich Dammert and Richard A. Dammert, project of a cast iron bridge to be erected across the river Weser at Hamelin, 1829 (NHStA 13b/Hameln 9pm)

Being not very sure about the reaction on their proposal from the beginning they presented two alternative designs, either on each side two or even merely one segmental arch. Certainly the latter solution promised more advantages, but would be harder to achieve by the means contemporarily available with the domestic ironworks of the Harz or at Uslar in the Solling near the Weser about 80 km upstream the construction site. Compared to timber cast iron was though the more resistant material which allowed longer span and beyond that a less arched superstructure. This again also meant that the ramps could get a minor gradient whereas the pitch could remain rather low. Additional arguments offered in favour of cast iron bridges were underlining that they would be rather light and cheap structures needing only quite a short time for both prefabrication and erection. If an iron bridge would not serve its purpose anymore, its components moreover either could be reused elsewhere or might fully be recycled in a foundry as scrap for new castings (LBA 1594.3 [1828], 9v–11r).

In spite of all these merits the project of a cast iron bridge never would be executed. It was destined to fail in the same way as the related project of a 28m spanning cast iron bridge over the river Innerste at Hildesheim (LBA 1594.3 [1824], 2v–3r). Albeit the idea to erect such a bridge in this commercial town passed by the road from Brunswick to Hamelin still was pursued for several years by the royal Hanoverian administration of the ironworks at Rothehutte in the eastern part of the Harz because its positive effects on employment, meanwhile Prott, however, had put his mind to build a suspension bridge across the river Weser instead. In his report handed over to the General Board of Roads in August 1829 he pointed out that unlike the cast iron bridge as designed by the Dammert brothers a suspension bridge would not need any river pier and in the case of a military conflict a couple of carpenters easily could prevent a crossing of the river by dismanteling within a few hours slowly the bridge deck (NHStA Hann 109.1028 [1829], §§ 3, 4, an 6).

Looking to the exchequer Prott underlined the rather low budget a suspension bridge would require. As its construction materials primarily would be iron and stone such a bridge promised «a durability of centuries». Merely the wooden bridge deck would need constant but not very expensive repair and therefore a continuous flow of tolls could be expected. Because the bridge would «suspended above the river» it certainly could be assumed that it never might be damaged by even the worst flood desaster or ice motion. Prott supposed besides that an absence of river piers would improve flood protection also of the city itself (NHStA Hann 109.1028 [1829], 1 and 3).

Concerning the question, if at Hamelin a «wire bridge» or a chain bridge would to be preferred, taking the bridges «recently built across the river Rhône near Serrières and Tournon» as an example, Prott plead at the moment for the former. To achieve a safe load of 42 tons he estimated its material requirements at merely 18.6 tons of iron wire less than 4mm in diameter, 12.5 tons of wrought iron, and 3.1 tons of cast iron which in his view altogether could be supplied by the state-owned ironworks of the domestic Harz. By a letter sent in late September 1829 to the General Board of Hydraulic Engineering Prott again urged the necessity for an immediate handing over of the bridge from the municipality to the state and then start on doing the preparational work (NHStA Hann 109.1028).

Although Prott's letter actually had been of crucial impact in launching the project it would take, however, some six years of an intense debate in many authorities were presenting their opinion or respectively their opposing views. By a memorandum of February 1830 the General Board of Hydraulic Works would lead off. To promote again the proposals by the Dammert brothers the board reminded that there would have been meanwhile good experiences with many cast iron bridges in England, France, and other countries, whereas there still would be a lack of such a certainty regarding suspension bridges. Albeit the board recommended the book published in 1824 by Henri Dufour on his iron wire suspension bridge at Geneva as a basis for further assessment, however, the memorandum was emphasizing that there still would have been almost nothing known about the impact changes in temperature, particularly frost, shocks, or lightnings, could made. Beyond that there also could not be discerned any component able to compensate even only one of the cables in the case of its rupture. Thus the board finally felt constrained to warn against the «great danger» a suspension bridge generally might imply. This fear also was supported by the impression

that this type simply was too much a novelty and its special demands of elasticity would not to be met by domestic iron reputed more for its temper if not its brittleness (NHStA Hann 109.1028 [1830]).

In contrast count Munster heading the Hanoverian government some month later, in November 1830, joined the expertise made by Georg Ludwig Friedrich Laves (1788–1864) who in his function as the director of the Board of Surveyors had pointed out that a suspension bridge would bring about economic benefits because of timber savings as well as of more employment in domestic mining and local crafts. Beyond that, Laves had continued his statement, it also would match very well with the beauty of the Weser valley (NHStA Hann 109.1028 [1830]). Until June 1833, however, it remained still unsettled if either wire cables or chains, either flat or round rods, should be applied. When George Wendelstadt (1790–1860) who, already prior to 1820 working with the General Board of Roads as an engineer and in 1826–30 being responsible for the design and erection of the remarkable viaducts near Einbeck, Northeim, and Munden (Schwartz 1989, 53), in 1832 was put in charge of the Hamelin project, he at first had to deal again with the old timber truss bridge there. By his report submitted in September that year he only could state an advanced stage of dilapidation.

Whereas Prott in his quotation presented three weeks later still was speaking about a «wire cable bridge», he would have changed his mind during the following spring. By his memorandum made in early June 1833 he eventually appeared being convinced that at Hamelin a «chain bridge» would be the best solution. Wendelstadt on the other hand would explain it by his final report of November 1933 referring to foreign models in meantime proved successful (NHStA 109.1028). Prott who in 1834 was mentioned as a subscriber of Franz Joseph Gerstner's handbook of mechanics (Gerstner 1834, 3: end papers w/o p.) in its first volume also dealing in detail with suspension bridges (Gerstner 1831, 1: 253 and 449), when he read it apparently got both the decisive inspiration and all the information needed.

Gerstner (1756–1832), since 1789 professor for mathematics at the university of Prague and in 1806 there the founder and first director of the Politecnic Institut, carried weight as an authority on both theory and practice of mechanics. Together with his son Anton (1793–1840) as early as the beginning of the 1820s, he conducted experiments on domestic iron wire, bar iron, and wrought iron chains as materials useful to suspension bridges (Ferjenèik and Hruban 1992, 543). As chairman of the Bohemian Society of Sciences in 1825 he gave a special lecture on his experiences, illustration it with the model of a chain bridge. As a conclusion he thus would rank «suspension or chain bridges among the more important subjects of recent mechanics and architecture» and meanwhile «the glory in having realized the largest and most perfect structures of this kind belongs to the Englishmen» (Gerstner 1831, 2: 449).

Developing a Bridge Design by Adaptation

When Prott had to defend his project for a last time in September 1836 he could derive an advantage from quoting the British experience as being confirmed by Gerstner. He had to refute the objections previously raised by the government building surveyors Hagemann and Mosengel that a chain bridge might not really be appropriate. In this regard they particularly had referred to the collapsed Pont des Invalides over the Seine in Paris. It was designed by Henri Navier (1785–1836) who by his «Rapport et Mémoires sur les ponts suspendus» published already in 1823 had described a fundamental theory on the design and calculation of suspension bridges. Albeit thus the doubts were to be taken seriously, Prott putting the rhetorical question «what at the end all these collapsed bridges» would prove, however, confidently answered that it would prove nothing more than the examples of all the stone arch bridges being collapsed already before (NHStA Hann 109. 1029, 30). Referring to British leadership he pointed out that neither the chain bridges on the Holyhead Road across the Menai strait and at Conway designed by Thomas Telford (1757–1834) nor the chain bridge since 1827 crossing the Thames at Hammersmith in nowadays London had done so (HNStA Hann 109. 1029, 32 and 50).

In particular this bridge designed by William Tierney Clark and in 1824 examined by Telford, not only for Prott, but also for many of his contemporaries soon had become the most sophisticated «model for a chain bridge» (Heinzerling 1868/69), 73). When Prott commissioned Wendelstadt in 1833 to draw up the

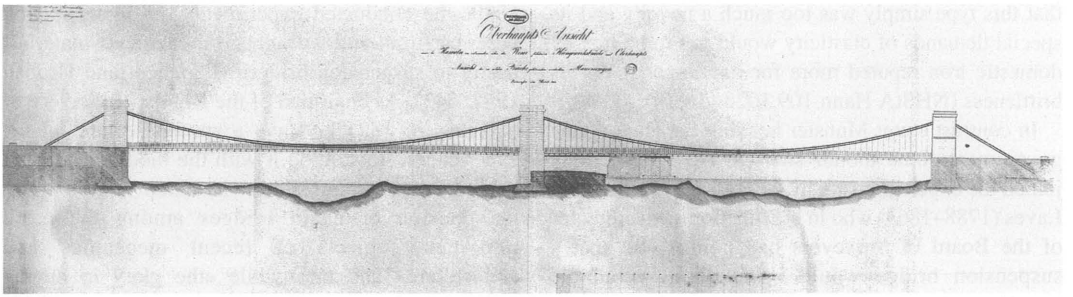


Figure 2
George Wendelstadt, project of a suspension bridge across the Weser and the masonry for a new holm bulwark, designed in autumn 1833 (NHStA 13b/Hameln 3k)

design for the Hamelin bridge it thus was suggested as the essential pattern to follow. Wendelstadt, however, was not allowed simply to copy the Hammersmith bridge just as he could not join implicitly Gerstner's descriptions. On the contrary he had to adapt it to the peculiarities of the site and the technical potential being available at the domestic ironworks. Wendelstadt thus was to detail the structure of the bridge and to fix the dimensions of every of its components as well as he was to make sure that the forgers and foundrymen of the Hanoverian ironworks, who never before were occupied with such an order, really would be able to prefabricate them in a proper precision and without any material fault. But not at least he had to close gaps in his own experience and comprehension of some particularities in the mechanics of suspension bridge structures.

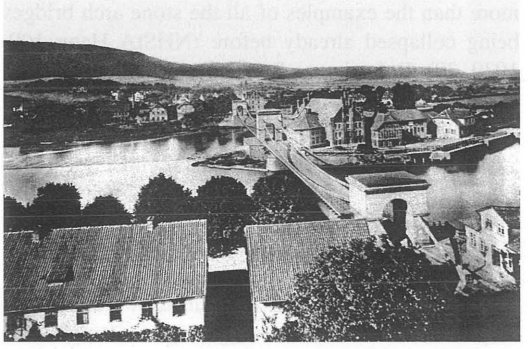


Figure 2a
The Hamelin chain bridge as looked in direction to the west, photograph, about 1880 (Hamelin Historical Museum)

Like Prott also Wendelstadt in this regard mainly had to rely on technical literature. Apparently both of them never had visited one of the suspension bridges since 1824 built at several places in the German Federation, neither the still existing footbridge by Johann Georg Kuppler over the river Pegnitz at Nuremberg following the pattern of Samuel Brown's Union Bridge at Berwick as in 1822 described by Robert Stevenson (Stevenson 1822, 116), nor the bridge at the Prussian ironworks of Malapane in Upper Silesia in 1827 constructed in a similar design, or the road bridge across the river Regnitz at Bamberg in Bavarian Upper Franconia designed in 1828 b y Franz Joseph Schierlinger (Schepe 1987, 163). Probably they also did not hear anything about the projects drawn up by the Prussian district architect Hermann Eberhard who in 1824 was commissioned by the government and had suggested to build across the river Weser at Hoxter either a three span cable bridge following Navier's proposals or chain bridge as being described by Stevenson (Grunsky 1998, 109). Quite obviously the reason was that Eberhard's suggestions soon would be rejected as it was the same with Peter Joseph Krahe's 1826/27 design of an asymmetric cable bridge to be erected over the river Oker at Brunswick (Dorn 1997, 51 and 318). They both would vanish for many decades into the respective filing cabinets.

By their career, however, Prott and Wendelstadt actually had not been unprepared. Both they were familiar with mathematics as well as with mechanics and each of them disposed of his own experience in civil engineering. While Prott, born at Hamelin as son of an artillery officer, after 1803 had worked in

England as a lieutenant with the engineering corps of the Kings's German Legion on the layout of fortifications, Wendelstadt, who was born at Wetzlar as son of a physician, first had studied chemistry at Marburg in Hesse. In 1813 he joined the Hanoverian army as an officer within the engineering corps, then in 1815 was released from duty to take up studies in science at Gottingen, before he finally was going to become virtually the head of every bridge building project to be executed for the Hanoverian state (Scholl 1978, 49 and 64).

The main difference to the Hammersmith bridge Wendelstadt had to consider, was that the Hamelin bridge needed three piers instead of only two. Whereas both piers of the Hammersmith bridge each were standing in the river near the embankment, Wendelstadt decided to place the central pier on the upper bulwark of the mill and lock holm and to integrate both the lateral piers just into the straight line of the embankment (NHStA 13b Hameln 3k [1833]). As the deck of the Hamelin bridge, its crossbeams as well as its planked surface entirely should be of timber, the whole structure would be specifically lighter than its English counterpart. Therefore the chains as well as the pairs of their cast iron bearing chairs, each of them to be mounted on one of the piers, also were to be more slightly dimensioned.

Considering their stitch Wendelstadt had studied besides the Hammersmith bridge also those of Paris, Bamberg, and the Menai Strait. Whereas the weight of the chains at Menai made 1300 and at Hammersmith 1050 tons, at Hamelin, however, it would not exceed 378 tons. Here also the chain stress was adjusted of merely a quarter of that to be met at Menai or Hammersmith. The safety factor, on the other hand, was equalized to that of the Menai bridge, in both cases raising by 25% above that of the Hammersmith bridge (NHStA Hann 109. 1029 [1836], 139). For the stitch of the Hamelin bridge itself Wendelstadt in a way was compromising between Navier on one and Telford or Clark on the other side. He took a relation of 1 : 12 for the stitch and chord length of the catenary, whereas that was about 1 : 9 in Paris, 1 : 13 at Menai, or even 1 : 15.5 in London (NHStA Hann 109. 1029 [1836], 127). A crucial point to be minded by Wendelstadt was that the chains were to cover all three piers without interruption between their anchorings on both sides of the bridge. As it also would have openings of different span, Wendelstadt paid special attention to rollers being more resistant and softer running in their bearing chairs on top of particularly the central pier than those at Menai or Hammersmith. To fix the hangers at the eyes of the chain bars he preferred screws instead of bolts like for instance Clark did (NHStA Hann 109. 1029 [1836], 152).

Beyond finding the solutions for structural adaptations Wendelstadt, however, still remained dependent of the capabilities of the state ironworks at Uslar. To clear the imponderables he had to make templates for each of the various kinds of forgings requested in particular for the chains. As it even though still remained uncertain, if each of all these components would achieve the same homogeneity, Wendelstadt first had to test about forty proofs on the

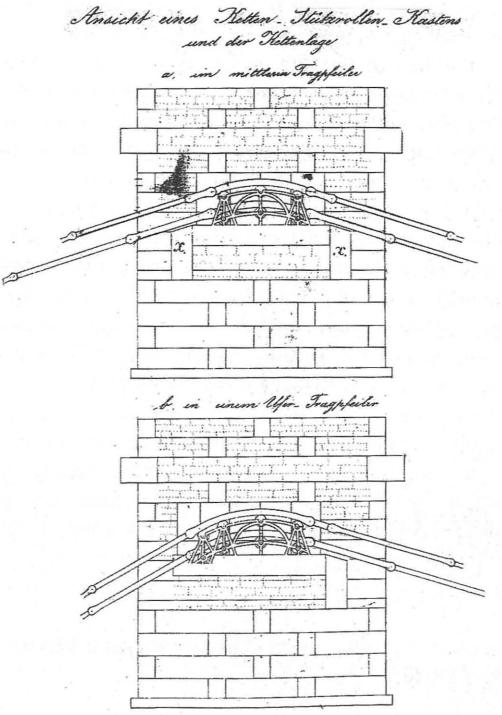


Figure 3
George Wendelstadt, view of a chain roller bearing chair and the chain position, a) in the central pier, b) in a bank pier; right part of a draft presenting the cross and longitudinal sections of the Hamelin suspension bridge piers, autumn 1833 (NHStA 13b/Hameln 4pg)

tensile testing machine at Carl Anton Henschel's engineering workshop in Cassel (LBA 1594. 4 [1836], 7v and 21v) before it could be decided, if each chain was to comprise «8 and 9, or 9 and 10 flat bars» as Prott had noted in a letter to Wendelstadt (NHStA Hann 109.1046 [1836]).

Regarding the bearing chairs Wendelstadt had oriented on the elasticity modulus according to Thomas Tredgold, regarding the flat bars for the chains on that according to Telford (LBA 1594. 4, 22r and 23v). For the forgers at Uslar ironworks, the Sollingerhutte, it was, however, hard to meet these measures because every component there had to be prefabricated on a water-powered belly or tail helve. The material was wrought iron refined by traditional Harz methods on from an alloy of charcoal pig iron originating from two different kinds of ores. Refining was made in two steps, first forging crude bars which then were to be bundled and welded together. Here the main problem was to prevent welding splits.

In total both refining forges of the Sollingerhutte had to supply 2204 flat bars of seven different shapes and sizes altogether summing up to 1235 tons of wrought iron. The eyes of the flat bars were to be drilled out. If the bars should be brought into a curved shape this had to be done by forging but not simply bending them and if the tolerance of about 1.2mm would have been missed the respective part had to be touched up by filing it (LBA 1594, 4, 11v). To protect the iron parts against corrosion they were covered with charcoal tar. Besides the flat bars 250 hanger rods, about 200 bolts of three different types, and various other wrought iron components had to be supplied to the construction site where the last parts would arrive only in December 1838, mainly on barges. Just the prefabrication of the chains was to take the Sollingerhutte 21 weeks (LBA 1594, 4, 88r and 162v).

Quite a Practical Success but Rather Minor Perception

After the chains were mounted until March 1839, the Hamelin chain bridge finally could be opened to traffic in late August that year (NHStA Hann 109. 1047). A first sweeping repair would be necessary not before 1851, but then only was to concern the timber components of the deck, in particular the cross beams. George Luttich, who after having finished his studies in technology, chemistry, and construction engineering at the Superior School of Industry at Hanover already had worked as Wendelstadt's resident engineer, suggested that cross beams of riveted wrought iron plate now should replace those of timber. The surface of the deck, however, as well as the longitudinally strutting parapet would be renewed in timber again (NHStA Hann 109.1029 [1851]).

The Hamelin chain bridge remained on its site until 1895 when it was to be dismantled, because the deck and its passage through both triumphal arch piers had become too narrow related to the meanwhile increasing traffic. Its center pier on the holm between both arms of the river, also stood too close to the directly neighbouring flourmill. This mill had been enlarged and needed more space at its loading platform as well as a more convenient ramp to the bridge. After a new cable-stayed steel bridge was opened to traffic, Wendelstadt's chain bridge was transferred to Hessisch Oldendorf, a small country town about 20 km downstream where it remained until it was blown up at the end of Word War II.

With the completion of the chain bridge in 1839, Prott, as its initiator, had been appointed an honorary citizen of Hamelin, and the bridge itself shortly came to be seen as the «largest and finest bridge in Germany» (Deurer et al. 1841, 11). Albeit no special publication on it appears to have been published, the bridge soon became widely known outside Hanoverian circles. Only weeks after the Hamelin bridge was opened to traffic, Wendelstadt was invited to deliver a design, together with a cost of estimate, for a chain bridge across the river Neckar by the city council of Mannheim in Baden.

The debate which subsequently arose at Mannheim and lasted about two years was in many respects similar to the earlier debate within the Hanoverian bureaucracy. In 1824 William von Traitteur (1788–1859), who then was working as an engineer and «innovator of Russian architecture» in Saint Petersburg (Fedorov 2000), where he made the design for a couple of chain bridges across the canals, had already proposed a chain bridge based on Telford's model at Menai Strait. His suggestion was rejected as it was, in 1835, the project for a stone arched bridge (Deurer et al. 1841, 5). As a result of the debate, around 1840 a final decision had to be made between

the offer of a French company to erect a cable suspension bridge similar to those constructed earlier in France and Switzerland, in particular like the one by Chaley across the river Saane at Fribourg, and the suggestion for a chain bridge by Wendelstadt whom at the end the majority of the city council decided to appoint. He became head of a team with Luttich again as resident engineer, and the Hanoverian railway engineer Adolph Funk (1819–89), who just had returned from England where he had met the Stevensons, Isambard Kingdom Brunel, and others, and who afterwards would become head of the Hanoverian corps of railway engineers (Luttich 1858; Scholl 1978, 95, 107, 186, and 200).

Wendelstadt in 1834 was to change his position as a military engineer when the General Board of Roads became a civil body and in would retire as road construction councilor at Stade in 1856. Since Hanover was going to build her railway net, road construction became of secondary importance. Mayor bridges, too, solely would be to design and to construct as railway bridges. In most cases, however, these bridges either were not as spectacular as it was the Hamelin chain bridge during the 1840s, or they were, in particular after 1866, built on the base of standard design. Their number raised and it became usual that their construction was executed by specialized firms like Louis Eilers established in 1871 at Hanover. As the Hanoverian State Railways were taken over by Prussian authorities in 1866, when the kingdom was annexed as a province, the more prominent bridges like that on the line between Luneburg and Schwerin crossing the river Elbe near Domitz were to be designed by the Prussian engineer John William Schwedler (1823–94) or his collaborators. All this made that Wendelstadt and his work very soon was overshadowed and at the end going to be neglected. On the other hand, however, meanwhile considerable changes also were to be stated. At least since the mid 19th century the heyday for wrought iron chain bridges everywhere was over and only in some really prominent cases bridge building would occupy an entire bureaucracy or touch a broader public by mainly its aesthetics. Finally in this regard it should not be neglected that the communities of engineering officers, architects, and noble officials inspired by the ideas of late enlightenment, characterizing the period around 1800, by the alternation of the generations was going to fall apart around 1850 at the latest.

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Historical Examples of Early Reinforced Concrete Structures. The Viaduct of Corso Italia in Bari: a Hypothesis for the Reuse

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Giuseppina R. Uva
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The Viaduct of Corso Italia in Bari was one of the first realizations in Europe of a superelevated railway using the reinforced concrete technology. Built in 1915, it is an outstanding example for the simplicity and effectiveness of the structural solution. Light and elegant, it is more than one kilometer long, and was built in only eight months by Porcheddu Enterprise, employing the Hennebique patent for the constructive system.

Appreciated as an artwork in its genre by the contemporaries, it is nowadays a significant historical example, showing the high technological and formal level of excellence achieved in the field of concrete construction.

The Viaduct is located in a strategically central area of the city, but unfortunately its immediate surroundings suffer a condition of urban decay. The situation is threatening to get worse, since a plan of general reorganization of the railway junction of the city provides the abandoning of that rail branch.

A question about the structural and functional rehabilitation of this work arises, and the discussion of the case study opens quite a few interesting points of reflection and investigation. In fact, many buildings and constructions belonging to the first decades of the twentieths century are present in our cities, and there is an urgent need of maintenance and rehabilitation for these pieces of work so rich in historical, architectural and cultural significance.

It is nowadays acknowledged that concrete is not an everlasting material. Despite of the fine and accurate quality of the work, this technology is subject to the deteriorating action of time even more than masonry is. Hence, it is particularly important to study in detail the historical examples, and to recognize the characters and the technical details of the solutions if we wish to keep the trace of the history and preserve the memory of the architectural and structural buildings of the '900. In this paper, a hypothesis for the reuse will be presented, and some general problems related to the diagnostics and the rehabilitation of historical R.C. constructions will be discussed.

The development of RC technology and the Hennebique patent

There is a number of historical antecedents to the reinforced concrete, and indeed concrete in itself has the same ancient and noble roots than masonry and stone constructions. Nevertheless, these precedents had only a negligible influence on the events that marked the end of the Nineteenth century and decided the beginning of a new Age for construction, within that second Industrial Revolution that was disruptively breaking into the world scene. Indeed, the appearance of the reinforced concrete system, unlike the previous building technologies, can be considered to be the fruit of a brilliant «invention» [4, 5] and not the result of a smooth and gradual development.

This is demonstrated also by the proliferation of patented systems: one for all, the one registered by *Monsieur Francois Hennebique*, whose name will be eternally bound to the development and diffusion of the new material. He himself contributed, in a certain sense,

to create the myth of the Ingenious Inventor, not without a cunning sense of business. The reference is to a popular anecdote according to which the entrepreneur *Hennebique*, while building a house in Belgium for his client, *Mr. Madoux*, happened to witness a terrible fire destroying a nearby building. So, he had a brilliant flash of inspiration and thought of a fireproof floor, made with a brand new material: the reinforced concrete. The slogan of the trademark became, in fact: «*Plus d'incendies désastreux*». Actually, it was the birth of an extraordinary climb to success for the man and the enterprise bringing his name.

More then the originality or the intrinsic superiority of his patent in comparison with the rival firms, the key of success was the great ability in the business strategy (actually, many features of the patent he used to display as personal ideas were present in previous elaborations).

On the one hand, he created a very effective organization, a net of agents and dealerships worldwide spread (by 1908, he had 42 affiliates in Europe, Africa, Asia and America) that can truly be considered an «ante litteram» franchising.

On the other hand, he acted a successful strategy of advertising and diffusion within the technical, academic and political circles. He promoted technical meetings and discussions, conferences (he was the organizer of the first conference on reinforced concrete), invited professionals, academicians and politicians in the building yards, founded a technical journal (*Le Bèton Armé*) on which even used to broadcast some disastrous failures of his rivals. What is certain, is that in the course of a few years (from 1892 to 1909) he realized 20824 projects, among which 1300 bridges. The unbroken success of his works strengthened his fame. As he himself liked to say: «*my buildings speak for me*».

The calculation method

The design of the structural elements subjected to bending moment is a peculiar feature of the Bureau Hennebique. Even if it was actually incorrect, the successes obtained in the practical application seem to demonstrate the effectiveness of the procedure. By all means, this should be ascribed to the great sensitivity and experience of the inventor, who was able to envisage mechanical phenomena still unknown at that time.

The method was based on the equal sharing out of the work between the concrete and the iron. A half of the bending moment was absorbed by the concrete, and a half by the reinforcements. The position of the neutral axis was an unknown of the problem, to be determined by en equilibrium equation between the half moment and the concrete stress (considered uniformly distributed and equal to *25 kg/cm*^{2}). Then, the correspondent equation applied to the steel allowed the determination of the minimum required area (assuming that the steel stress and the distance from the neutral axis is fixed).

The Porcheddu Company

One of the dealerships of Hennebique trademark in Italy, the most representative and important, was the Company G. A. Porcheddu, operating in Italy from 1894 to 1933. Endowed with a modern and efficient organization, this professional office was able to develop autonomously the design activity: it is worth remembering that the Company released a number of original patents, and employed for the first time a light mixed roof made of r.c. and bricks, the forefather of a type that today is the undisputed ruler in the Italian building scene. The company was the protagonist of great and significant projects in Italy. The most renowned is certainly the Bridge *Risorgimento* on the *Tevere* River (Rome). It spanned with a single bay a distance of one hundred meters and held the primacy of the longest r.c. bridge for many years.

Mostly present in Piemonte and Northern Italy, some projects were carried out in the rest on the country too, above all in the hard years of the first world war, when it remained the only Italian agent for the Hennebique trademark.

In Southern Italy, there were very few works of the Porcheddu Company, and the only bridge is a railway viaduct located in the city of *Bari*.

The Viaduct of Corso Italia, Bari

The History

At the beginning of 1915, the opening of a new *1200* kilometers railway line connecting some Italians regions (Puglia, Calabria, and Basilicata) was

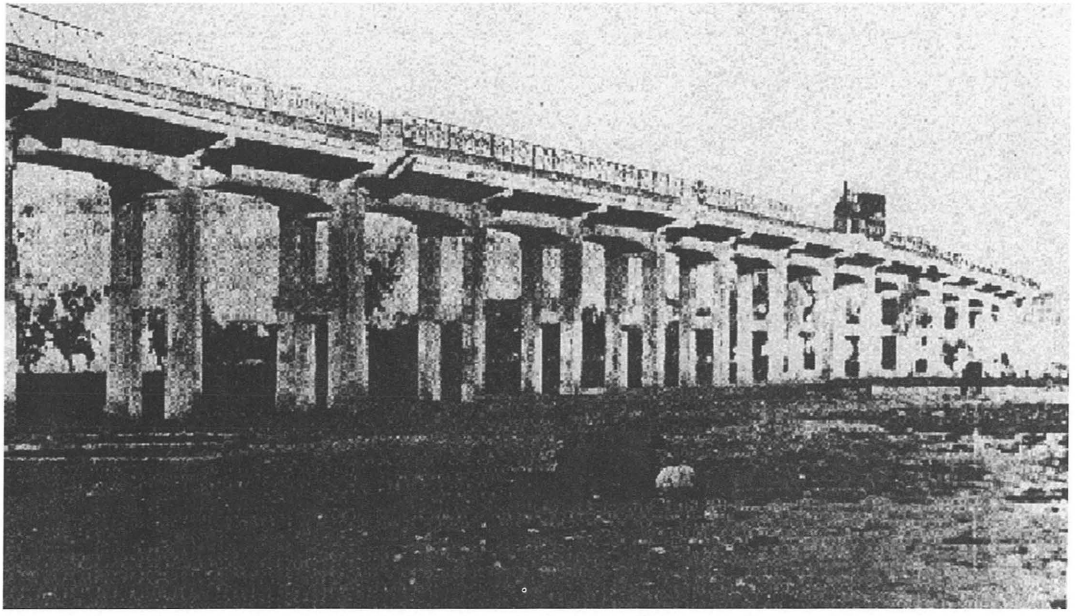


Figure 1
Photos of the viaduct during the construction: the arc viaduct and the concrete flyover [6]

announced. The event was really significant under a social, economic and political point of view. In fact, it established, at last, a connection among territories geographically isolated and set apart from the economic scene since that time.

The enterprise was hard, and was the occasion for the realization, in Southern Italy, of a significant example of the rising technology of reinforced concrete. In fact, while other bridges and viaducts of the line were traditional masonry or steel constructions, one of the branches —the 280 km long-line Bari-Atena— started in the city of Bari with a concrete flyover track «*just like those built in the big foreign metropolis*» (newspaper of the *Touring club Italiano*, N. 1, January 1915 [7]). It was more than one kilometer long, and indeed it was one of the first examples in Europe of a railway line set over a concrete viaduct. Surely, it was the longest in Italy and represented a technological milestone. It brought in Southern Italy that revolution that had invested many European countries and, with the coming of a new modern material, would have radically changed the Structural Design and the Architecture, as well.

Technical features

The viaduct was designed and built by the Porcheddu Company, which completed the work in only eight months of restless activity, despite the difficulties and restrictions imposed by the war (fig. 1, 6). The official test of the flyover, 1038.80 meters long, took place on the 23 of July 1915, and was welcomed by the local press as a symbol of the modernity and technical progress.

The essential and simple (but nevertheless elegant) design revealed itself to be successful, both in the static performance and in the formal solution. The project, registered at the National technical Office for constructions in the May of 1912, provided a structural scheme with equal bays about 9 meters long. Every four bays, a joint breaks the continuity of the system, allowing the free thermal expansion of the spans. Moreover, this structural arrangement, tested with excellent results in many different works by the Porcheddu Company, perfectly fits the theoretical model of calculation (fig. 2).

The structural section that sustains the plank (*3.40*

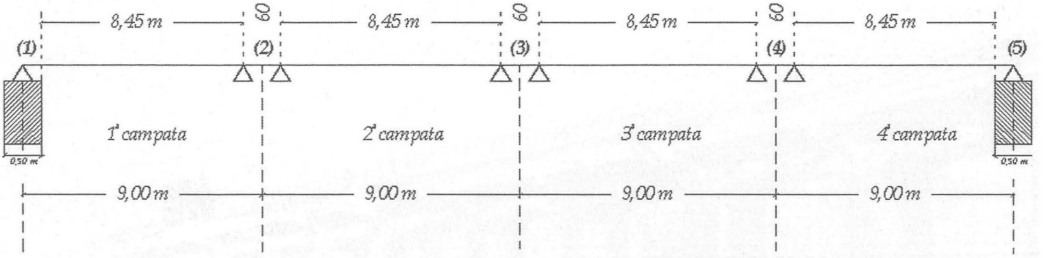


Figure 2
The structural model adopted for the calculation

meters wide) is made up of two rectangular beams (*60 cm* wide and *100 cm* high, on average) located just under the axis of the rails, and superiorly connected by a thick slab (11.5 cm) in order to guarantee the collaboration and the transversal stiffness (fig. 3). Finally, the system is completed by a protruding slab (that has a slant of *2.5%* for a rapid draining of the water) and by two edge beams holding the rail bed.

The vertical support is supplied by couples of columns founded over a concrete plate. The supports are doubled at the dilatation joints (fig. 4) although founded over the same plate.

All the design was performed in accordance with the in-force law (the *Regio Decreto* issued in 1907). The work of the materials was kept under the limits prescribed by the law, that is to say, a limit stress of *1000 kg/cm²* for the tension in the steel (*800 kg/cm²* for the shear) and *40 kg/cm²* for the compressed concrete (threshold attained, moreover, only in one case), that was made with a measure of *300 Kg* of cement for each cube meter of mixture.

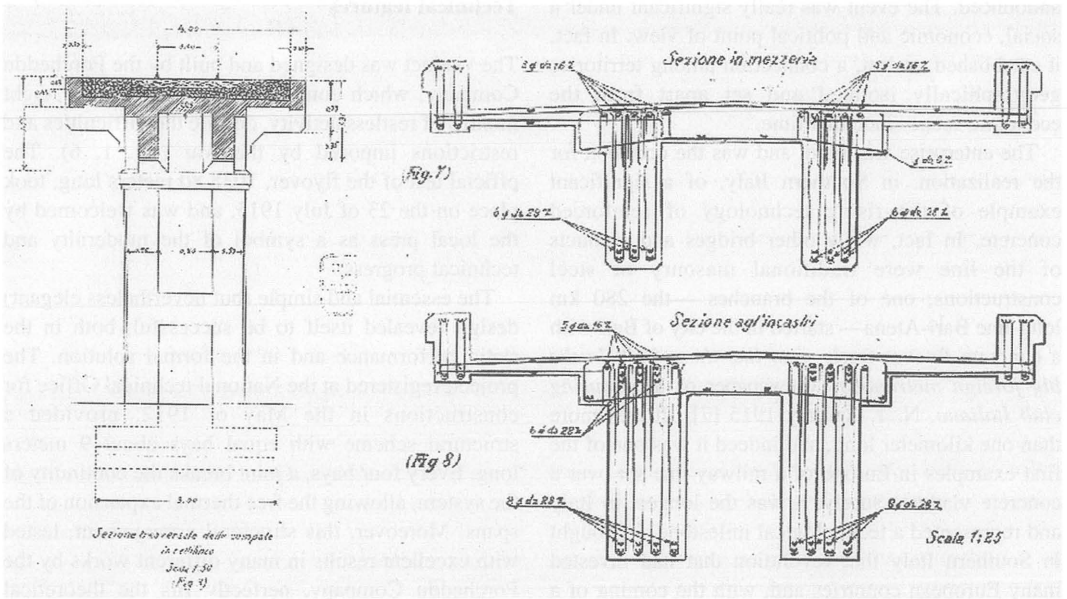


Figure 3
Section of the Viaduct; detail of the reinforcements and brackets [6]

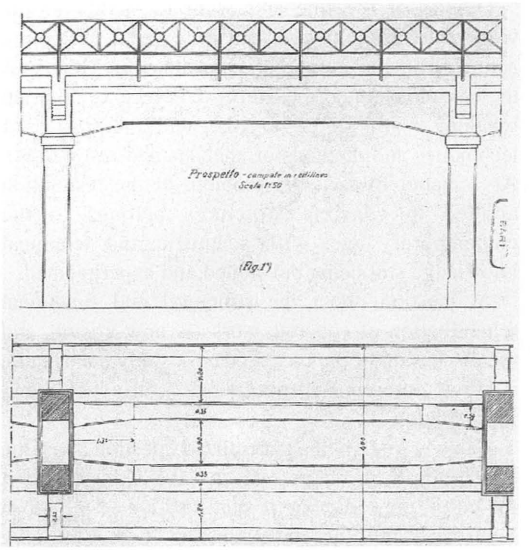


Figure 4
Prospect and plan view of the Viaduct [6]

From the review of the original project [1], it can be seen that all the calculations were made in accordance to the current methods (indeed, not very far from the admissible stress method that is still used in Italy nowadays), as required by the law. In particular, a 4-bays scheme (fig. 2) was adopted. The dead load was estimated as *4900 Kg/m* (including the structural load and the roadbed), while for the live-loads two typical trains were considered, distinguishing a flexural action from a shear one and obtaining an equivalent distributed load (*6820 Kg/m* and *7500 Kg/m* respectively).

In order to account for the dynamic effects induced by mobile loads, a *25%* increment was applied to the mentioned loads, leading to the design values of *8525 Kg/m* and *9375 Kg/m*. The maximum bending moment and maximum shear were found from the Winkler tables, for a continuous beam of equal bays, on five supports.

In the static verification, two main beams were considered, having a rectangular section of *60x100÷120 cm*. The connecting slab was considered to be collaborating for a width of *270 cm*.

Considering that the prescriptive value for the homogenization coefficient n was *10*, and applying the standard calculation for the design and

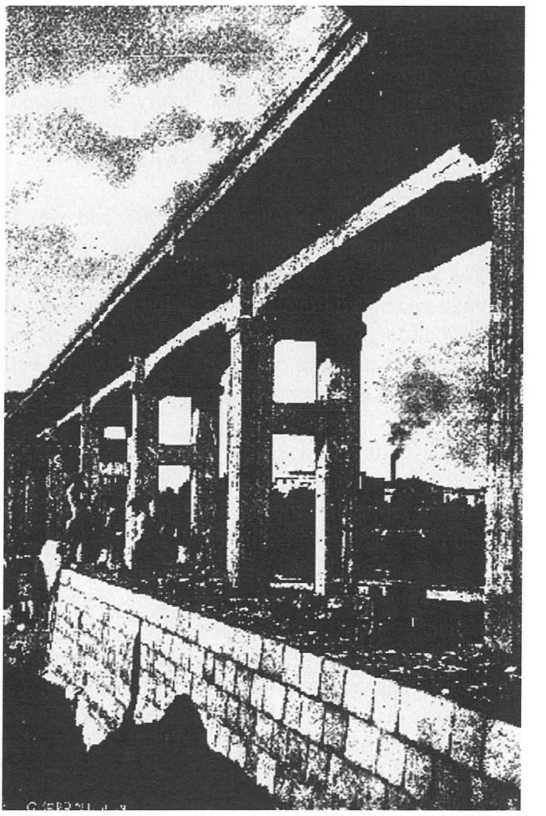


Figure 6
Crossing of the stream Picone: picture of the time [6]

verification of the section, it can be seen that a minimum quantity of steel of about *150 cm²* and an approximate height of *110 cm* are required. Actually, in each main beam 4 Φ 30 straight bars were adopted, and 5 additional bent bars (Φ *35*) were arranged in order to help the maximum stress zones (total amount: *152.76 cm²*). With these entries, the position of the neutral axis results to be at 30.72 cm from the superior border; the stress ratio is *37.8 Kg/cm²* for the concrete and *802 Kg/cm²* for the steel.

The Role of the Patented System after the regulations issuing

At the beginning of the century, the first national technical laws were issued, under the boost of

numerous collapses. So, the end of the age of the pioneers of concrete arrived, and a field until then characterized by the personal undertaking and ability in conquering the market was finally reorganized. Many European countries soon adopted rules for the concrete constructions (1903, Switzerland, 1904 Germany, 1906 France).

In Italy, the regulation arrived in 1907, and even if in the beginning it only concerned public works, it marked an important stage, since no reference to the patented systems was made at all. All that was needed for the building was to be designed according to the law requirements, to be correctly carried out and well supported by a good reputation and experience of the company.

In spite of this new scenery, the use of patented systems still persisted in the professional practice. Well established and tested technologies were still preferred and considered more reliable. The case of the Viaduct of Bari is a good example of this tendency, since the Porcheddu Company managed it according to an experienced procedure.

In what the distinctive function of the patent consisted in this example we can only guess, since the official project was drafted according to the new prescriptions, definitely far-off from the «secret» method of calculation used for so many years by Hennebique.

Anyway, this circumstance well demonstrates the peculiar characterization of the reinforced concrete technology as an outbreaking invention, to such an extent that the forerunners and their inventions held for a long time a leading position.

On this subject, a curious remark can be done. By applying the celebrated method of the «*half-and-half momentum*», we can find that the amount of steel needed for the section is just the same that is foreseen by the modern method.

The structural rehabilitation of concrete structures: the case study

The structural safety of *modern* R. C. building is nowadays a crucial exigency under many points of view. Even if in the common sense the reinforced concrete has been usually considered an indefinitely strong material, a forefront technology —in a word— a paradigm of Modernity, it is nowadays acknowledged that concrete is not an everlasting material.

Despite of the fine and accurate quality of the work, this technology is subject to the deteriorating action of time even more then masonry is. Moreover, the consciousness of the intrinsic defects brought up by aging is still scarce (together with the practice of techniques and methods of analysis and restoration). As a matter of fact, the problem of the restoration applied to concrete structures belongs to the contemporary age, with scientific and technical knowledge still being developed and experimented.

A question about the structural and functional rehabilitation of concrete works is now arising, and the discussion of the proposed case study opens quite a few interesting points of reflection and investigation.

There is first of all a generalized question about the interventions on a large scale in the existing fabric of the cities, the following re-qualification of the urban landscape and the management of the building heritage on the territory.

In Italy, both in the historical cores and in the outskirts, there is in fact a strong presence of r.c. buildings side by side with the traditional masonry constructions. The r.c. architecture ranges from the first realizations (at the beginning of nineteenth century) to the outbreak of the concrete technology and the related building trade in the 70's. Not always it is characterized by a quality of architectural expression and construction as well. In many cases, the eventual perishability of this material (phenomenon still unknown and unexplored at that time) has now become evident and calls for urgent recovery.

Anyway, this minor but widespread building represents a relevant part of the residential housing in the Italian cities, for which structural safety and functional rehabilitation stand as primary question of scientific, social and territorial interest.

On the other hand, a lot of r.c. works belonging to the first decades of the twentieths century have become a landmark of historical and architectural significance and can be truly considered as monuments of the *Modern.* Despite of the many problems of durability and maintenance suffered by the material «concrete», these structures, born at the dawning of the new technology, still survive and have shown even better performances then many subsequent examples.

It is particularly important to study in detail the historical examples, and to recognize the characters

and the technical details of the solutions, if we wish to keep the trace of the history and preserve the evidence of the architecture and the structural science of the '900.

Reinforced concrete: open questions in the diagnostics, safety assessment and structural rehabilitation

For r.c. structures, it is worth wile observing that only quite recently a knowledge of degradation and viscosity phenomena has been acquired, and the constructive detailing aimed at providing the quality of durability has been accordingly adopted.

Furthermore, it should be remembered that reinforced concrete works, from the origins (in the last decades of 1800) until the release of the first national technical laws (in Italy, the first one was released in 1907), were built by applying patented systems (i.e the Monnier or the Hennebique system). These patentcd systems were often a result of individual intuitions more than a fruit of a coherent and established scientific and technical knowledge. This is one of the reasons why many of the structures built in those years, and still surviving, could not be considered reliable with regard to the static structural safety, as it is presently intended.

As a last element, but crucial all the same, we should point out that, in spite of the availability of advanced and reliable methods for the numerical and theoretical modeling of concrete, the safety assessment is characterized by a strong level of uncertainty, because of the poorness of the data that can be acquired about materials, building techniques, constructive details.

In the professional practice this aspect is often disregarded, since an unconditional confidence is usually devoted to modern materials and structural types, to which the designer is used.

But also in this case, the a-posteriori comprehension of an existing object is a complex process, inevitably incomplete and defective. The designer himself, even if he will probably be able to make a reasonable approximation, will never rule the structural response of his creation. In no way the application of scientifically based models in the design of a structure can assure the agreement between the foreseen behaviour and the actual one. In the practice, structures always show more or less relevant deviations from the prediction, and an undiscerning trust in the theoretical model is possibly dangerous more then deceiving.

The difficult task of the diagnostics is, then, to mark out the history of the building, reconstruct the geometrical, physical and mechanical features of the construction as they were designed and as they were actually realized (number and position of the reinforce bars, general arrangement of crucial nodes and sections, mechanical properties and technological characteristics of materials used).

For those buildings dated back to the period of the first experimenters and inventors of the reinforced concrete, the further problem of identifying the structural type of the examined case arise. In fact, the large diffusion of many different systems in the period between the end of 1880 and the beginning of 1900 makes it difficult for technicians to interpret the building technique used.

The rehabilitation procedure is always a complex process, relying on an integrated path of preliminary knowledge, analysis, decision-making and action (architectural interpretation, experimental investigation and testing, analytical modeling, choice of the intervention tecnique). For the reinforced concrete it becomes particularly tricky for different reasons.

First of all, unlike ancient constructions, a rooted tradition in restoration and repair is lacking in this field: since a few decades only interventions on concrete buildings have been faced, and this problem has been received in the academic and scientific circles.

Whereas the peculiar feature of masonry is the relative facility in being dismantled and reassembled, concrete is a monolithic material, and once a specific shape has been realized, it is a serious problem to vary it, or to intervene subsequently. Repair techniques must account for these difficulties, and innovative materials and techniques are being studied and experimented (concrete or metal jackets, fiber reinforced polymers, etc.).

The structural rehabilitation of The Viaduct in 1975

In 1975, repair and refurbishment of the structures of the Viaduct were needed in order to guarantee the

proper functioning of the railway (that is nowadays still in use).

Actually, the largest part of the interventions performed were not so severe, and concerned mostly the damage caused by water seeping, such as the crumbling of rebar cover and steel corrosion. Only foundations were affected by a more intensive care and suffered a real structural strengthening, with the construction of a new external concrete coating and the placement of additional reinforcement bars. Anyway, this rehabilitation case was in the forefront of restoration technology, at that time, with regard to the materials used. In fact, in order to avoid discontinuities between the existing structures and the new layers, tixotropic and epoxy mortars, having a controlled shrinkage, were used (fig. 7).

Foundations: the ground was excavated, in order to completely uncover the foundations; a concrete coating was realized that included part of the piers, and new steel reinforcement bars were placed under the ground level.

Elevation structures (main and secondary beams, piers, slabs, cantilever beams and balconies) all the damaged concrete covering (both the one already detached and that inadequately adherent) was eliminated by hydro-demolition (using smooth water jets). After uncovering the existing rebars, the rust was mechanically removed and, where required, brand new steel bars were placed to substitute the unrecoverable ones. Before reinstating the concrete covering, all reinforcements were treated with inhibitor of corrosion and passivating products. Afterwards, a high bond electrically welded wire netting was placed on the plank and the side beams. The concrete gaps were filled in with the tixotropic mortar. Finally, in order to guarantee serviceability conditions, the entire plank was made waterproof with a special mortar layer and pvc outlets were placed to divert meteoric water.

Dismissed Infrastructures: a Proposal for the Reuse

The Viaduct is located in a strategically central area of the city, but unfortunately its immediate surroundings suffer a condition of urban decay. The

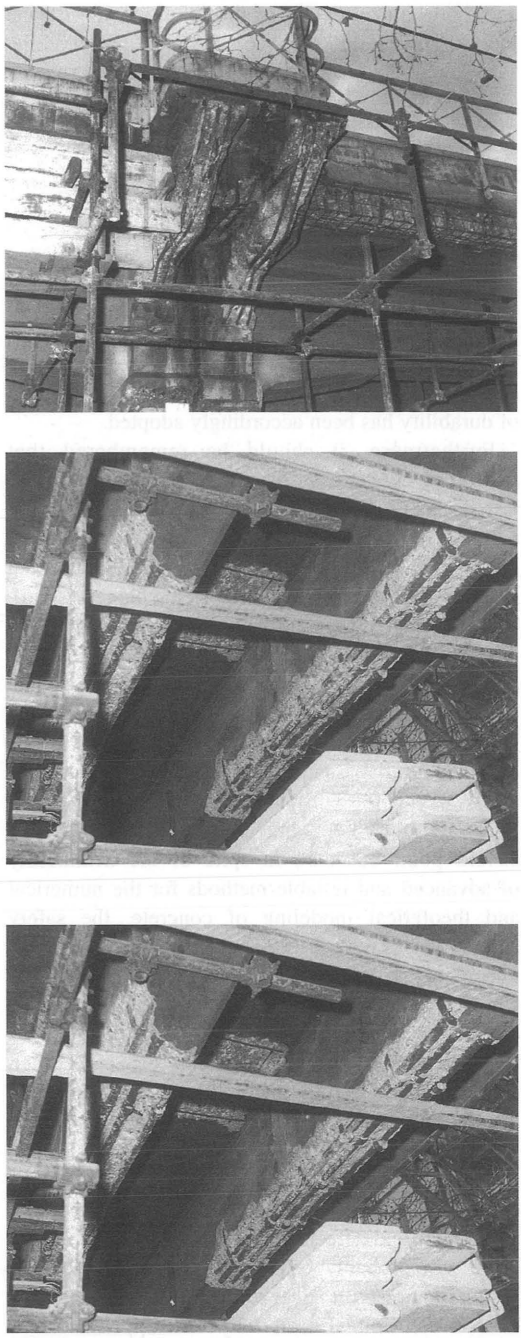


Figure 7
The structural rehabilitation in 1975 (Photos by Michele Mastrodonato)

image that the inhabitants of the area have is that of a place of ill fame and decline, spoiling the reputation of the neighborhoods.

In the last few years, a plan of general reorganization of the railway junction of the city has been conceived, that, when applied, will involve the abandoning of that rail branch. Once dismissed, the future existence of the Viaduct will be in jeopardy, considering also the negative image it has gained through the years, unless an alternative for its usage is not designed.

Indeed, the historical, scientific and cultural value of the concrete pieces of work of the early '900 is widely recognized. It is beyond doubt that they are worth to be preserved as a landmark of the rising and development of a new technology that, from its origins on, has been welcomed as an outbreaking innovation and since then has been associated, not always with impartiality, to the idea of Modern.

The case study of the Viaduct of *Corso Italia* in *Bari* is emblematic as regards to the exigency of retaining the cultural and historical evidence of an Age. The risk is to waste, under the pressing urge for a renovation and restoration of the City's look, a precious but still unrecognized heritage —like it happened, for example, for many ancient buildings under the hunger for modernity and renewal characterizing the urban growth in the 60th.

These remarks should not be intended as an unconditioned and extremist praise of the conservatism in Architecture. On the contrary, it is opinion of the authors that the historical value of a building just consists in the richness of the historical subsidence. The monuments, as we see them today, are the result of long vicissitudes; alterations and rearrangements in order to be adapted to the different usage needs and tastes of the users. Indeed, the possibility of suiting changeable requirements often decides the same survival of the construction.

The problem is, eventually, to solve the question —both formal and static— of the relationship with the preexistence, trying to breed the *raison d'être* of the construction.

The arc-viaduct and the flyover: a scenery for the city of Bari

The first part of the line is an arc viaduct in traditional masonry work, and is located nearby the central railway station, in a lively, commercial area. The rest of the Viaduct, and in particular the one-kilometer long r.c. flyover, is instead more marginal, and despite its closeness to the centre, is plunged in a residential district, far from the shopping and walking routes, that are diverted towards more attractive roads.

In view of the plans of urban restoration that involve this construction, and as an alternative to a possible demolition, a rethinking of the functional use of the viaduct, no more touched by the running through of the trains, can be proposed. Not only this proposal is aimed at preserving a construction we consider of scientific and engineering interest, but indeed can offer a real chance of development to that part of the city and bring a new life, just taking advantage from the presence of that structure that is so hindered at the moment.

A green haven spanning the city traffic

The idea is inspired by a similar case: *Le Viaduc des Artes*, in the XII Arrondissement of Paris. Part of the

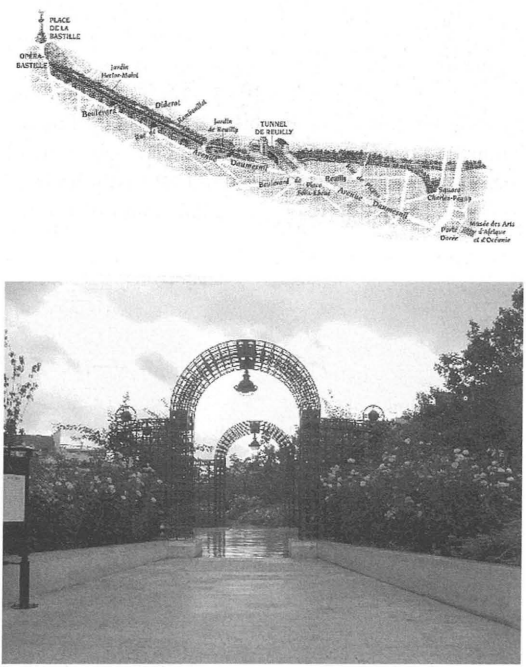


Figure 8
Le Viaduc desArtes and the Promenade Plantée

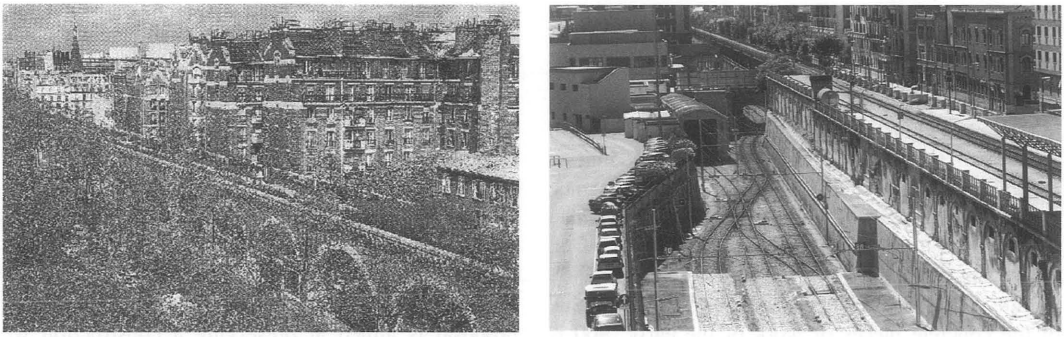


Figure 9
View of the Promenade Plantée (left) in Paris and view of the Viaduct of Corso Italia as it can be seen today in Bari (rigth)

Vincenne railway and cast off in 1969, this viaduct was divested to the Municipality of Paris in 1986.

In four kilometres flying 9.18 meters high over the ground level, the local administration has created a pedestrian precinct spangled with a sequence of blooming roof gardens: the *Promenade Plantée* (fig. 8). Among bowers, fountains and benches, the promenade is an invitation to live the city under a different point of a view, far from traffic jams and confusion. A thick green barrier gently protects the walkway, but nevertheless lets gleam through the life flowing far down. In fact, the project managed by the Municipality was not restricted to an operation of mere urban decoration, that could be easily doomed to fail, without having an actual spin-off for the district. Under the arches of the viaduct, 60 vaulted rooms house workshops and little handicrafts shops, in accordance with the craft vocation of the XII arrondissement (fig. 9–10). So, the Viaduct has become the showroom for jewel makers, sculptors, artists, embroiderers and lute-makers working in the calm of the ateliers made out of the restored bays of the bridge. And the impact on the quarter, before degraded and ill famed, has been very positive, even more than it was expected.

This is not an utopian, fantasy scenery. It's an actual case of a clever and useful management of the resources of the city that, on the track of this short theoretical reflection, could be developed and successfully applied to the proposed case study.



Figure 10
Under the arches of the viaducts of Paris and Bari, two similar urban scenes

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